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VEHICLE DYNAMICS PROGRAMS FOR ROADWAY AND ROADSIDE STUDIES

Final Report

UMTRI-98-20-1

Prepared for

Federal Highway Administration

Contract DTFH 61-93-R-00142

Michael W. Sayers

April 1999

UMTRI The University of Michigan Transportation Research Institute

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16. Abstract

The main objective of this project was to select among existing vehicle dynamics simulation programs and link them through a common database to commercial roadway CAD programs. The existing TruckSim and AutoSim technologies were selected and extended for this project to create a software package called VDM RoAD (Vehicle Dynamic Models Roadway Analysis and Design). VDM RoAD simulates the vehicle dynamics behavior of cars, trucks, and two-unit combination vehicles (tractor-semitrailers) on 3D road designs. The software runs under Windows 95 and Windows NT and shows results graphically with plots and animations. The software can be used by engineers who are not experts in simulation or even vehicle dynamics.

The new software was developed with the intention of adding it to an interactive highway safety design model (IHSDM) that systematically considers safety of roadway and roadside design elements in creating cost-effective highway design alternatives. Although VDM RoAD is designed to work with other parts of the IHSDM, further integration is not recommended because most factors of performance that are of interest to roadway designers do not require vehicle dynamics simulation. Vehicle-related performance measures are largely defined by lateral acceleration, which depends only on the kinematics that link roadway geometry and travel speed.

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METRIC (SI*) CONVERSION FACTORS

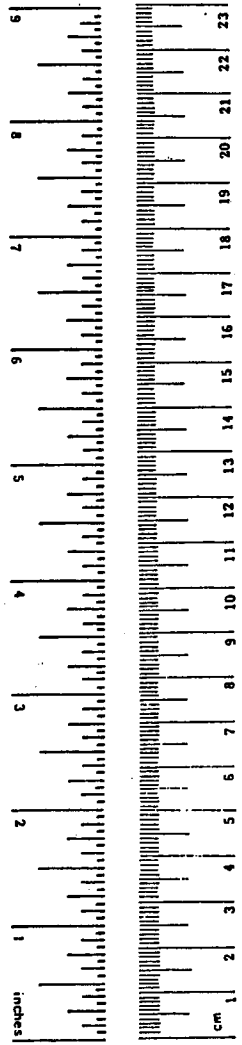
APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
AREA				
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.0929	metres squared	m²
yd²	square yards	0.836	metres squared	m²
mi²	square miles	2.59	kilometres squared	km²
ac	acres	0.395	hectares	ha
MASS (weight)				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
VOLUME				
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.0328	metres cubed	m³
yd³	cubic yards	0.0765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

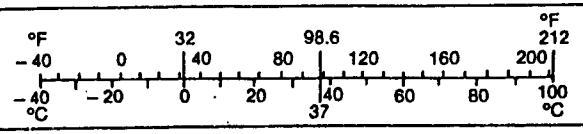


APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
AREA				
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
km²	kilometres squared	0.39	square miles	mi²
ha	hectores (10 000 m²)	2.53	acres	ac
MASS (weight)				
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
VOLUME				
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

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1. INTRODUCTION

In the late 1980s, the Federal Highway Administration (FHWA) assigned a high priority to research and development of better highway design practices and criteria. The goal of this multiyear program is to develop an interactive highway safety design model (IHSDM) that systematically considers safety of roadway and roadside design elements in creating cost-effective highway design alternatives. The computing environment is intended to serve several purposes. First, it provides a data structure for the convenient development of input and output data libraries. Second, it enables data to be shared between the different modules of this computing environment. Third, it encourages the integration of commercially developed and maintained vehicle dynamics, computer-aided design (CAD) and finite element analysis (FEA) programs into FHWA's research and design activities.

An integrated design process was conceived that would use modern computer technology to simultaneously take into account significant factors of performance and safety [*1*]. The road design is stored in a commercial CAD file format, such as Intergraph's MICROSTATION or Autodesk's AUTOCAD. As shown in Figure 1, other modules are envisioned to analyze proposed designs and provide the designer with rapid feedback to identify possible problems.

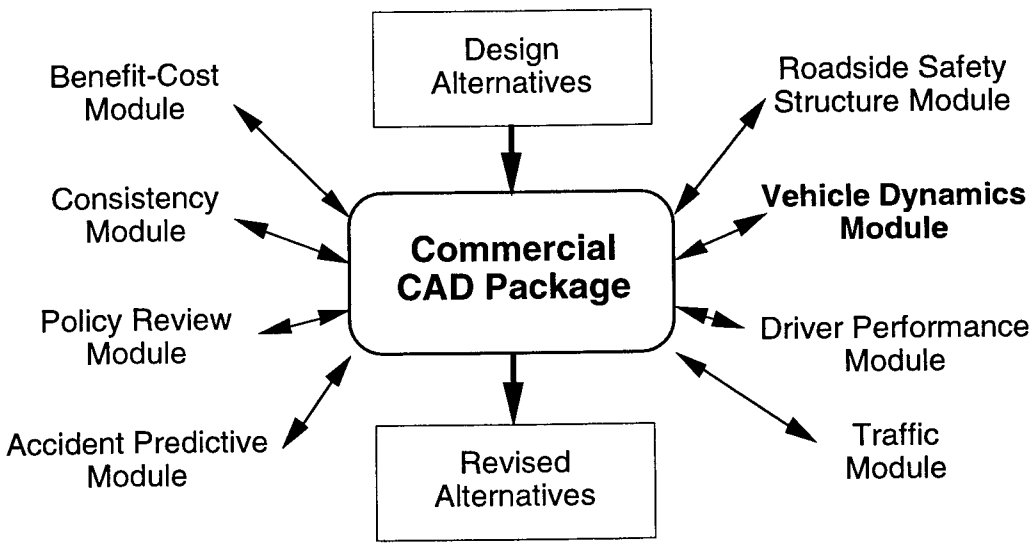


Figure 1. Concept of the IHSDM.

This report documents the research conducted at The University of Michigan Transportation Research Institute (UMTRI) under FHWA Contract DTFH 61-93-R-00142. The objectives of the research were to select vehicle dynamics models and link them through a common database to standard commercial roadway CAD programs. The software architecture is designed for flexibility to enable linking with a driver performance model in the near future. The design also allows integration with finite element and other commercially available modules.

Project Deliverables

The project involved the following deliverables (in addition to this report):

- The main deliverable is a comprehensive software package called VDM RoAD (Vehicle Dynamic Models Roadway Analysis and Design). VDM RoAD was developed to simulate the vehicle dynamics behavior of cars, trucks, and two-unit combination vehicles (tractor-semitrailers) on 3D road designs. This software runs under Windows 95 and Windows NT.
- A full description of VDM RoAD, along with instructions for its use, is provided in a 350-page reference manual, "VDM RoAD User Reference Manual Version 1.0" [2].
- Two copies of the commercial simulation program TruckSim were delivered. TruckSim supports vehicle dynamics studies that focus more on the vehicle and less on the road design properties.
- Two HP workstations were purchased for the project. One was shipped to the Turner-Fairbank Highway Research Center in May 1995 and the other has been used at UMTRI as an Internet server for road profiles and public-domain software maintained by UMTRI.
- UMTRI prepared presentations, software demonstrations, and an exhibit for the TRB-FHWA "3D Transportation Visualization and Simulation Symposium Workshop" that was held in Houston during May 1995.
- A UNIX program called RAPID COMBINE was created and delivered in 1995 to combine vehicle response properties with road design data and speeds.
- A UNIX version of the VDM RoAD was created. However, the UNIX version is less developed than the Windows version.

Organization of this Report

This report is intended to describe the project for which VDM RoAD was developed. The full documentation for VDM RoAD is provided in the user reference manual, "VDM RoAD User Reference Manual Version 1.0" [2]. Section 2 describes the VDM RoAD software. It has example applications and a short overview of the architecture. Section 3 covers the topic of how the vehicle dynamics models are integrated with road design data. Section 4 discusses how VDM RoAD can be integrated in the future with the driver performance module currently in development. Section 5 presents conclusions and recommendations for future integration of vehicle dynamics models within IHDSM.

An appendix is provided that discusses the topic of lateral acceleration. During the project it became apparent that some users were expecting the vehicle dynamics module to predict lateral acceleration. This appendix was prepared to explain why lateral acceleration is largely unrelated to vehicle dynamics.

2. THE VDM ROAD SOFTWARE

VDM RoAD is a marriage of vehicle dynamics simulation technology with roadway CAD technology. In just a few minutes, an engineer can simulate the behavior of a vehicle driving over several kilometers of a new roadway design. Results are viewed immediately. Plots of important variables can instantly identify trouble spots (station number) where excessive motions occur. Vehicle motions can be viewed with wire-frame animation. The software runs on Intel PCs equipped with Windows 95 or Windows NT. It is self-contained, requiring no additional programs or tools to function.

The most striking feature of VDM RoAD is the ease of use. The software can be used by engineers who are no experts in simulation or even vehicle dynamics. This contrasts with older simulation packages. Vehicle dynamics programs have traditionally offered mechanical engineers the ability to perform virtual tests on the computer to study the dynamics of vehicles in limited test conditions. Considerable expertise was needed in the fields of vehicle dynamics and numerical analysis. Further, the time needed to become proficient with simulation software has always been so lengthy that only the most determined engineers would become productive.

Overview of VDM RoAD Operation

VDM RoAD can be used to evaluate highway designs, as they would be experienced by different vehicles traveling over a variety of speeds. VDM RoAD includes twelve example vehicles from the *AASHTO Green Book* [*3*]. It also includes data sets for a car (Ford Taurus) and heavy truck. Those data sets were based on extensive laboratory measurements to support research at the National Highway Traffic Safety Administration (NHTSA) involving the validation of computer models of vehicle dynamics.

Figure 2 shows a screen dump of the main screen display in VDM RoAD. The pull-down menu lists some of the example runs that are installed. A user can browse through the database of VDM RoAD or use the menu to jump right to the results for a specific simulation run. For example, in the figure, the selected run is named **WB-12 (Alt 3 R Lane)**. This title was composed by a user and has not special significance to the simulation programs within VDM RoAD. (The title indicates that the run involves a vehicle called WB-12 running in the right-hand lane of a road design called Alt 3. WB-12 is a combination vehicle in the *AASHTO Green Book* made of a 12-foot tractor towing a 12-ft semitrailer.)

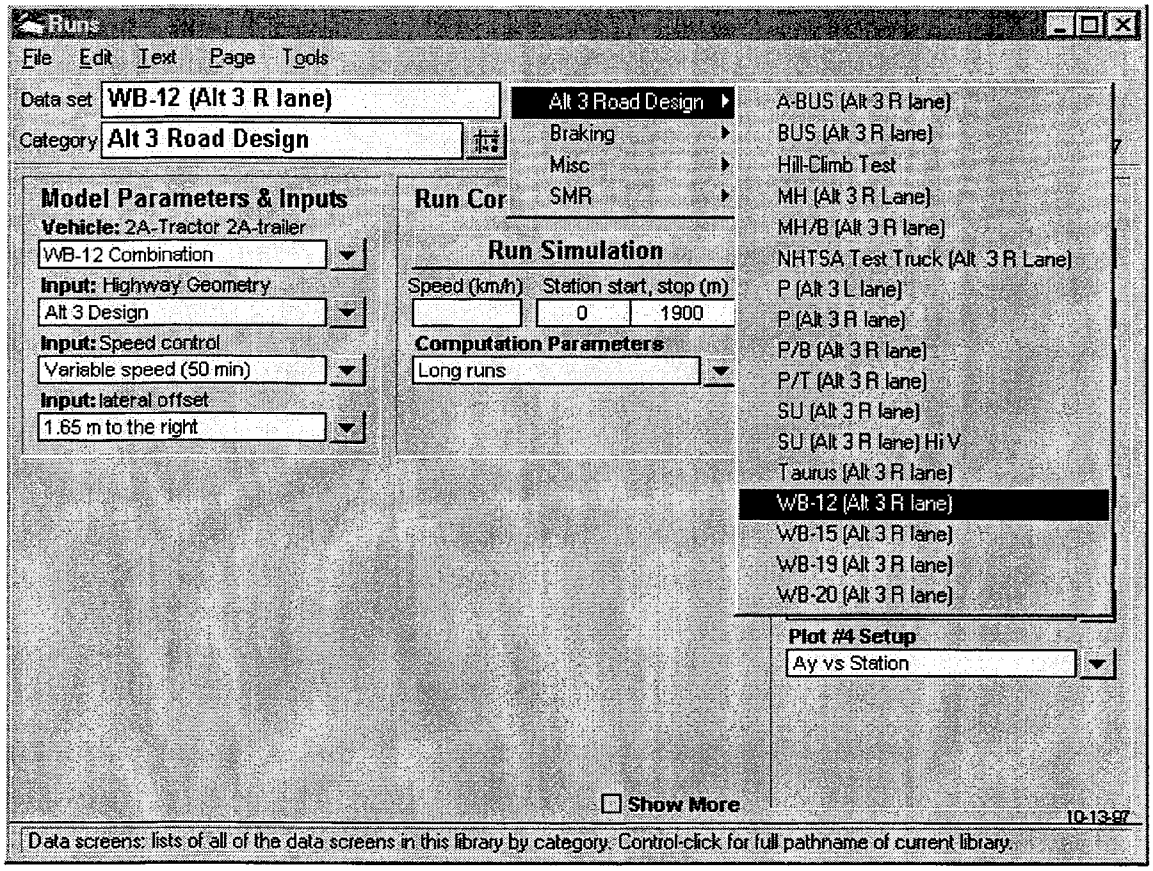


Figure 2. Example runs in VDM RoAD.

The **Runs** screen is shown again in Figure 3 with a different pull-down menu showing. The window contains three categories of user controls: inputs, the run, and outputs. On the left, under the caption **Model Parameters & Inputs**, are four links to various kinds of input data:

1. a vehicle (in the figure the vehicle is called **WB-12 Combination**),
2. a road (in the figure the road is called **Alt 3 Design**),
3. target speed (defined as a function of station number), and
4. target lateral position (also defined as a function of station number).

These four links are made by the user with pull-down menus. For example, Figure 3 shows the screen appearance when the button next to the **Vehicles** link is clicked. A pull-down menu appears listing all of the vehicle data sets that are available in a "library" of vehicles. In this case, the library contains combination vehicles involving trailers. A different vehicle can be selected from the library by clicking on the button to display the menu, then choosing a vehicle from the menu.

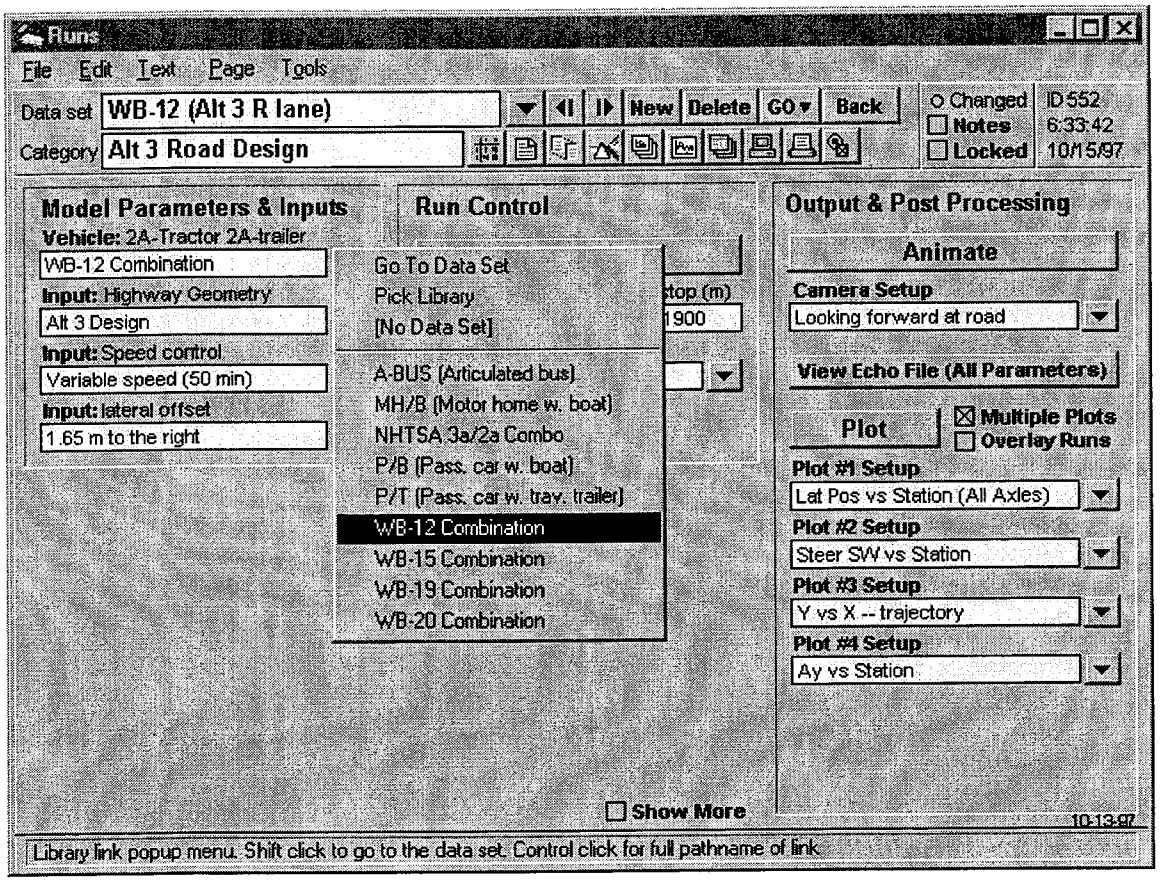


Figure 3. Example combination vehicles in VDM RoAD.

The next link defines the road geometry that will be used in the simulation. The data screen that defines the road geometry is shown in Figure 4. The road geometric data are described in a text file containing data in the IHSDM database format. The data screen shows the full pathname to the file (in the example, it is `D:\VDM_ROAD\ROADS\ALT3.IHM`). In addition to the pathname, the data set includes optional links to animation files that are used to draw the road geometry in the wire-frame animator program.

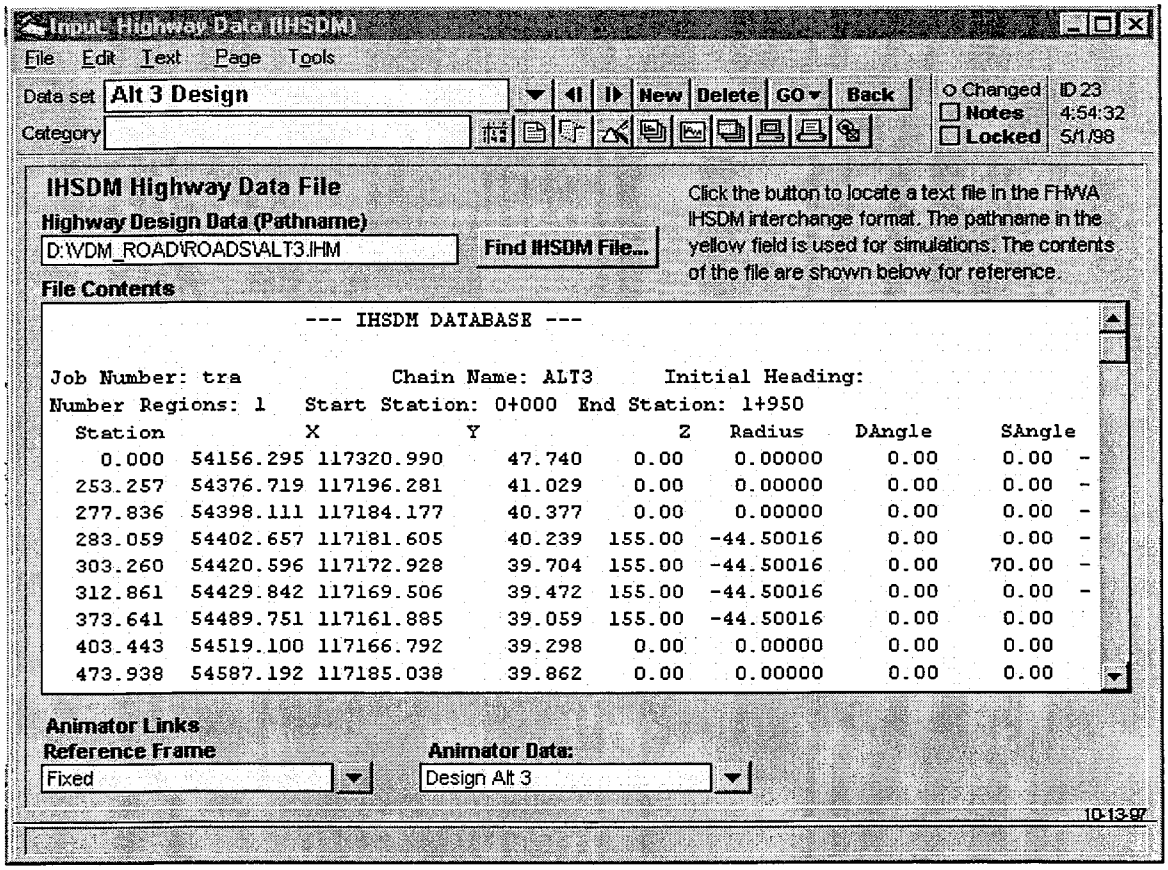


Figure 4. Road geometry.

Another simulation input is a speed for the vehicle. As shown in Figure 5, the speed is not necessarily a constant. The user can specify speed as a function of station number.

To make a simulation run in VDM RoAD, the user picks a vehicle, speed, and road, using the links in the left region of the **Runs** screen. The controls and settings used to run the simulation are in the middle of the screen (see Figure 2). There are fields for entering a starting and stopping station number. For the example run represented in Figure 2, the vehicle is initially located at station 0 and the run ends when the vehicle reaches station 1900. A button with the caption **Run Simulation** is used to make the virtual test on the computer, simulating the specified vehicle running down the specified road under the conditions defined by the links on the screen.

The mathematical vehicle models in VDM RoAD involve detailed nonlinear tire models and nonlinear spring models. They include the major kinematic and compliance effects in the suspensions and steering systems in cars and heavy trucks. The kinematical and dynamical equations are valid for full nonlinear 3D motions of rigid bodies. VDM RoAD uses closed-loop controller algorithms to steer the vehicle along the specified path and to drive at the prescribed speed.

The simulations run quickly, given the level of detail in the models. On Pentium-Pro computers, the programs run in real time or faster. In other words, a run simulating a two-minute test will finish in less than two minutes.

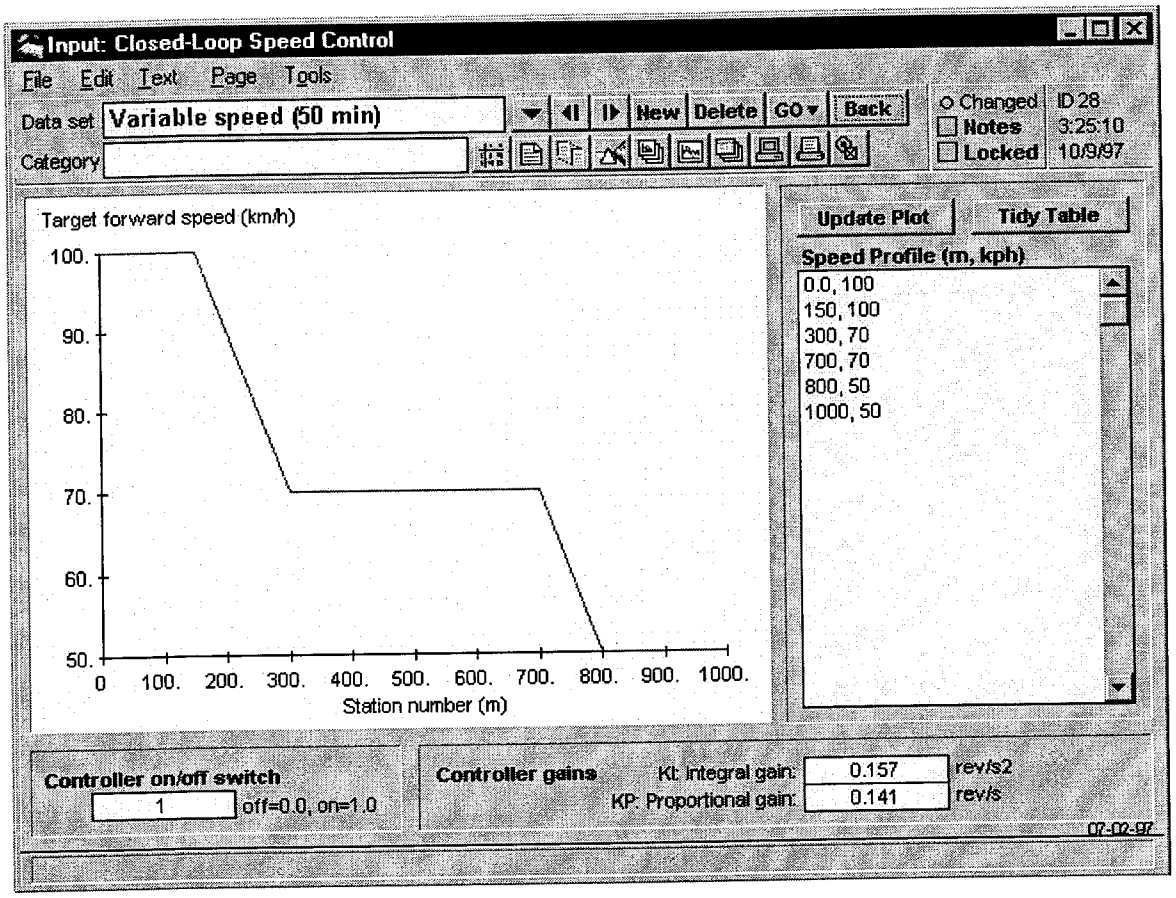


Figure 5. Target vehicle speed.

After a run has been made, the results are viewed using controls located in the right-hand portion of the screen (see Figure 3). For example, clicking the **Animate** button brings up an animation of the run, as shown in Figure 6. From within the animator, the user can view the vehicle behavior in real time. A slider control (lower-left part of screen) can be used to rapidly jump to any point in time. Other controls allow the user to change point of view, zoom in and out, and advance in slow motion.

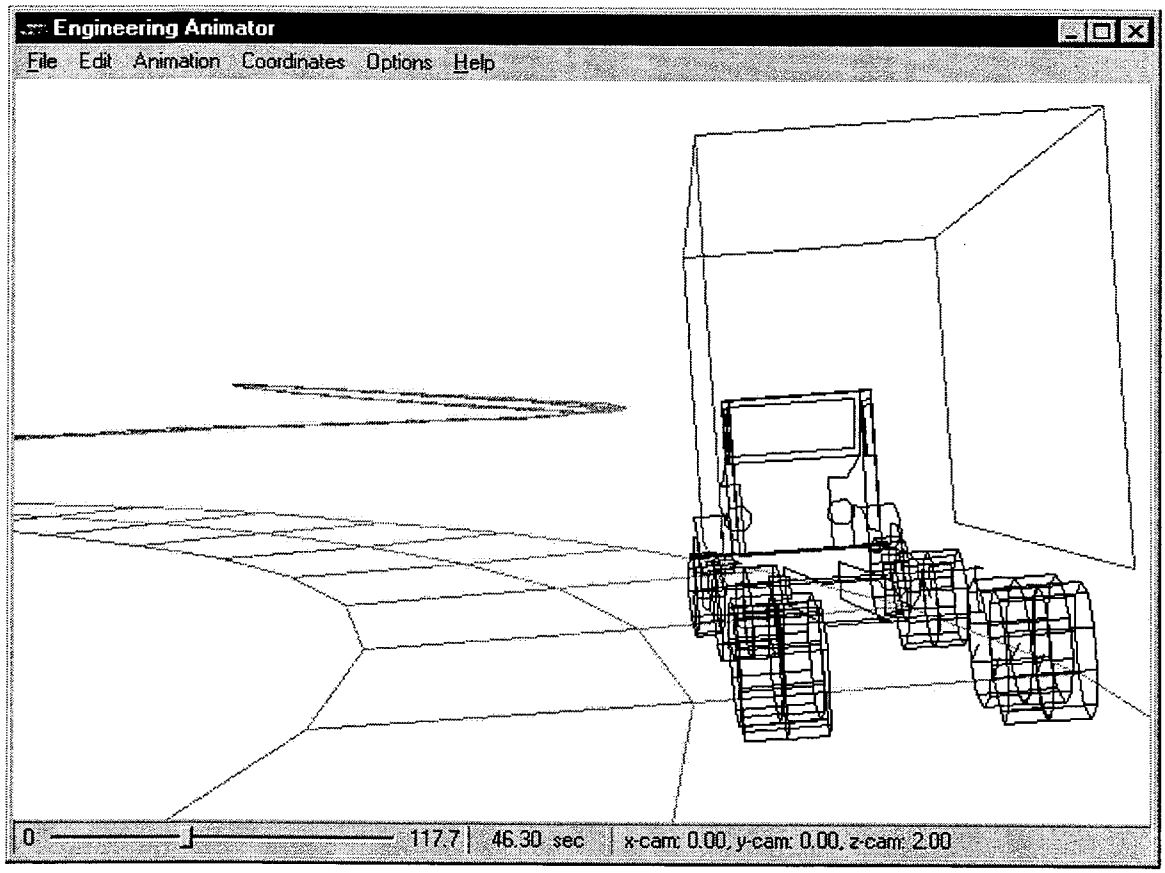


Figure 6. Animation of simulation results.

The user clicks the **Plot** button (also located in the right-hand portion of Figure 3) to view engineering plots of the simulation results. For example, Figure 7 shows four plots made this way. The upper-left plot shows lateral acceleration experienced by the tractor and trailer, along with the lateral acceleration defined by the road geometry and vehicle speed. (See Appendix A for a discussion of the lateral acceleration due to the road). The upper-right plot shows the steering wheel angle needed to navigate the road with the specified vehicle, speed, and lateral position. The plot underneath (lower-right) shows the tracking of each wheel in the simulated vehicle. This plot summarizes the tracking requirements for the combination of vehicle and speed for the entire section of road (station 0 to 1900).

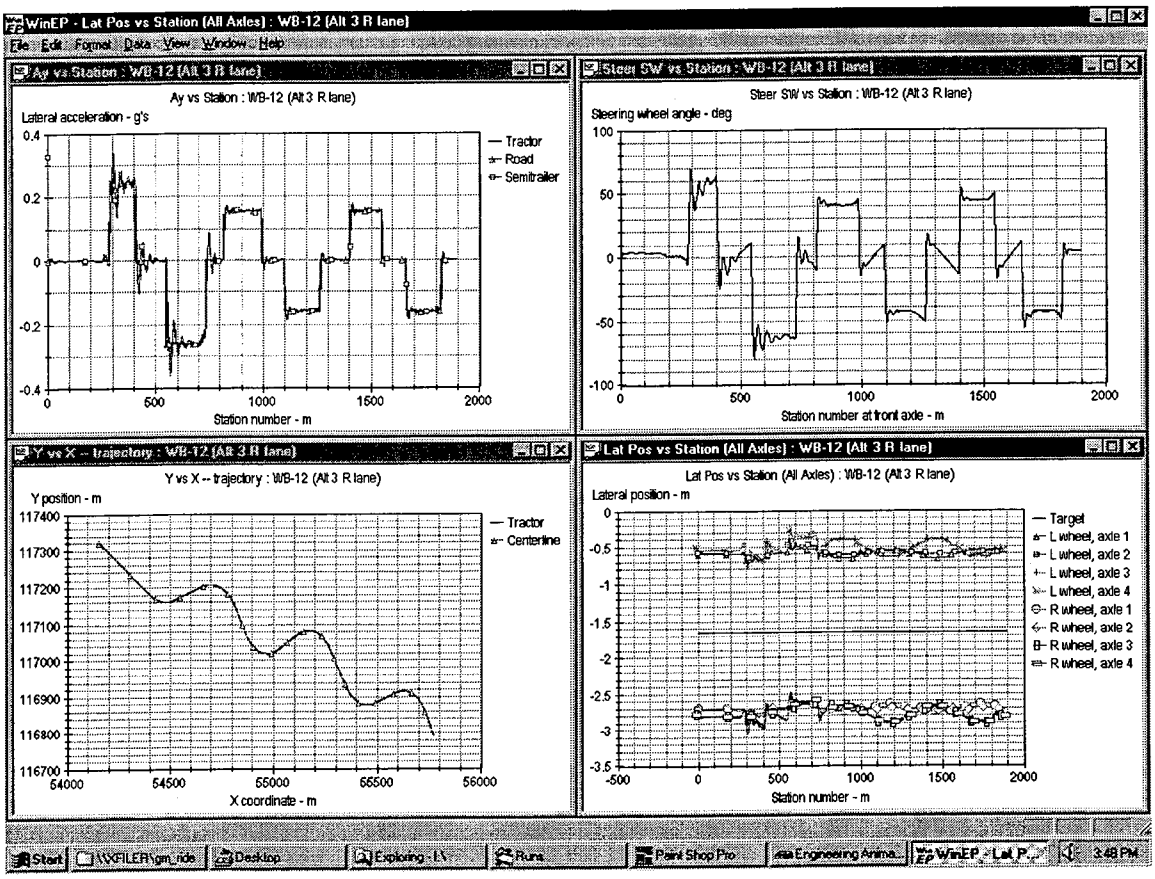


Figure 7. Example plots of simulation results.

Figure 8 shows four more plots from the same run. Here are plots of the vertical tire forces and the vehicle roll angles for the tractor and semitrailer. Vehicle speed is also shown, overlaid with the target speed, shown earlier as an input in Figure 5.

VDM RoAD includes more than 30 predefined plot setups such as the eight shown in Figure 7 and Figure 8. Further, users can define new plots involving any combination of the hundred or so variables stored on disk whenever a simulation is run.

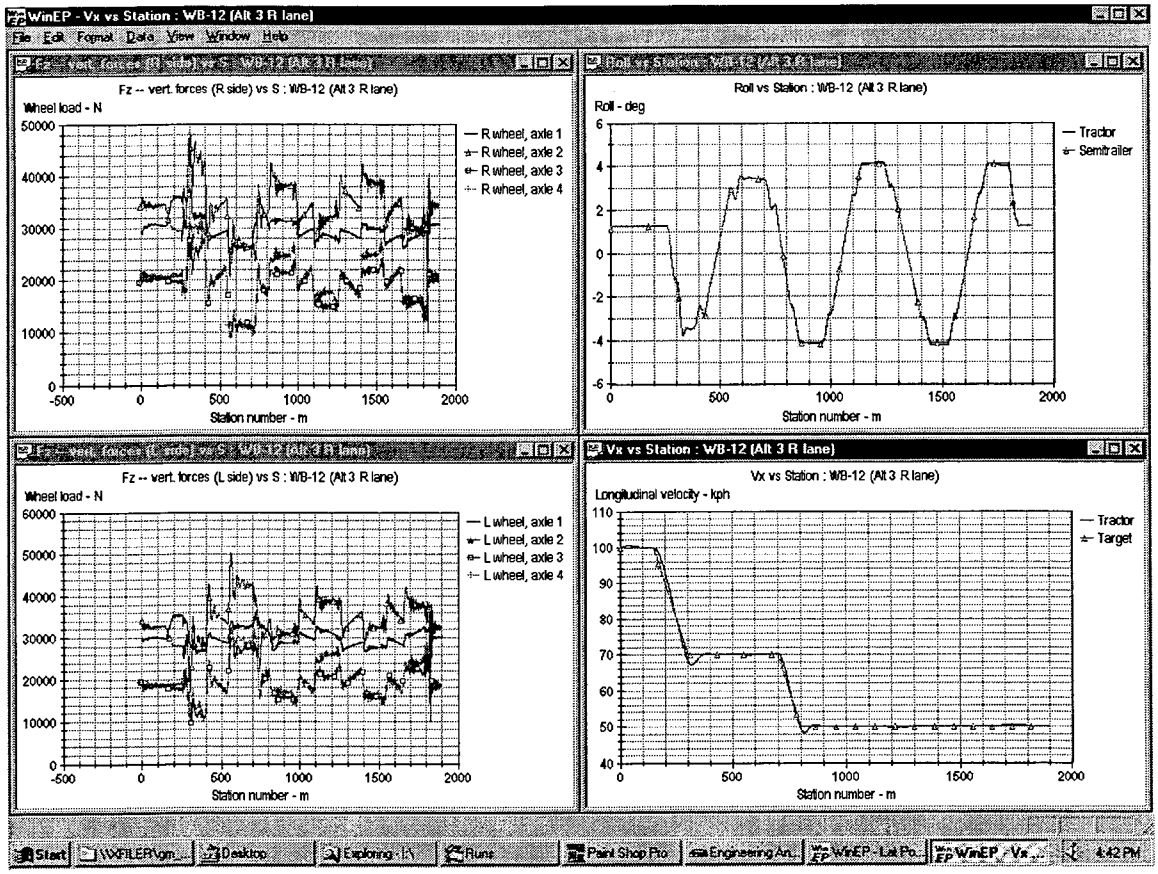


Figure 8. More plots for a simulation run.

Software Architecture

VDM RoAD is made up of four tightly integrated types of software that are shown conceptually in Figure 9.

1. Data screens serve as the primary interface to VDM RoAD. They contain vehicle model parameters, control inputs, run settings, and links to IHSDM files with road geometric data. The data screens are part of a database with many libraries of related data sets.

2. Simulation programs numerically solve equations of motion (i.e., mathematical vehicle models) to calculate output variables. The process of performing these calculations is called making a **simulation run**. These programs are applied automatically from the data screens when you click a "run button."

3. An animator shows the computed vehicle motions using wire-frame shapes for the vehicle and road. The user can view the simulated motions, zoom in and out with a virtual camera, and interactively move around the simulated vehicle to change point of view.

4. The Windows Engineering Plotter (WinEP) creates plots of vehicle variables as functions of time or as cross plots of output variables. This tool is used to view any of the hundreds of variables computed by the simulation models.

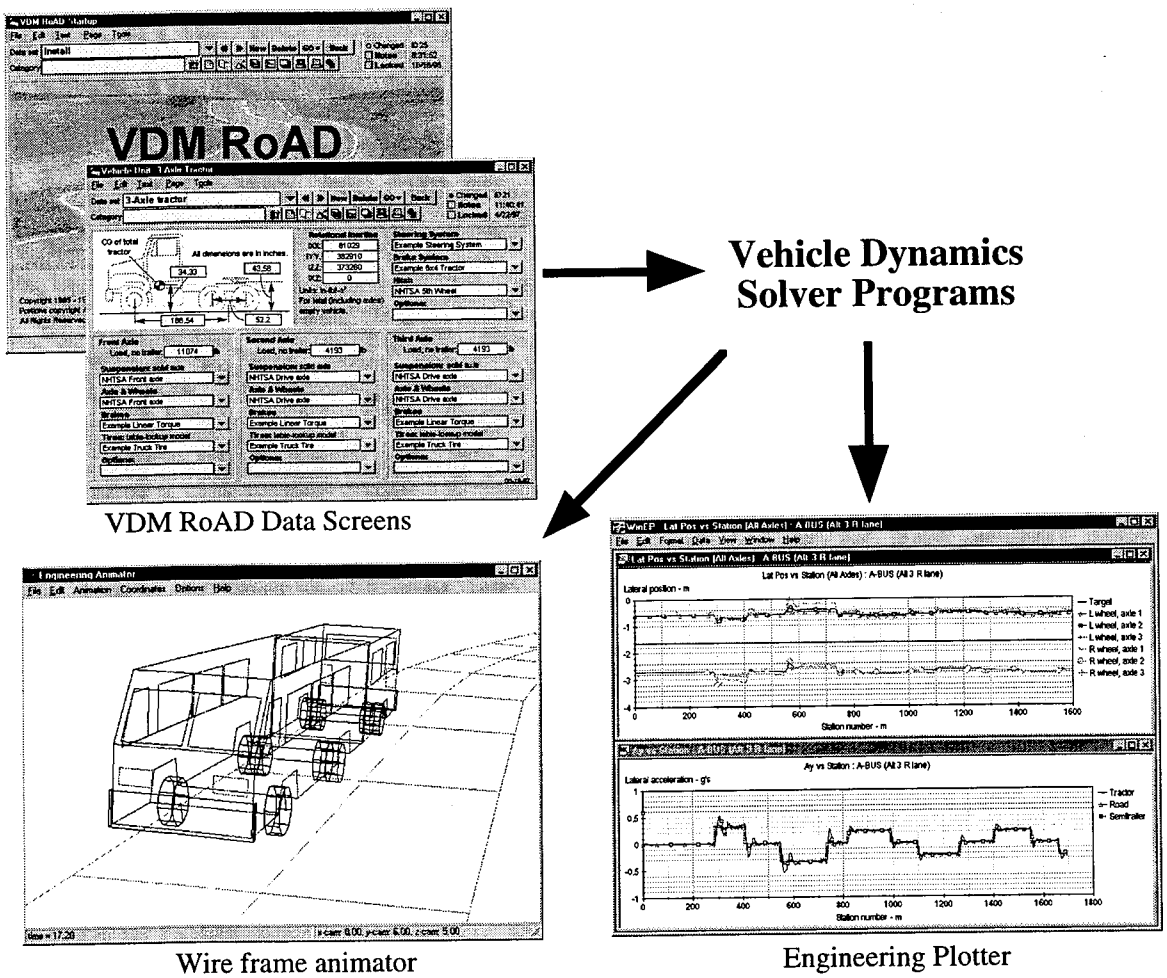


Figure 9. Four parts of VDM RoAD.

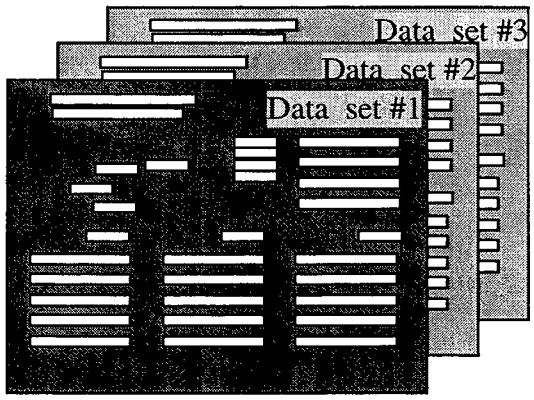
Most user interactions with VDM RoAD involve preparing data sets for simulation runs or viewing outputs of simulation runs. In either case, the user deals extensively with the VDM RoAD database. The database was programmed using a software package called ToolBook, available from Asymetrix, Inc. [*4*]. ToolBook is an scriptable object-based software development tool primarily used for preparing educational and multimedia material. It is also commonly used for prototyping graphical user interfaces for complex software projects.

In addition to VDM RoAD, other simulation packages have been prepared using the architecture shown in Figure 9. The architecture is called the simulation graphical user interface (SGUI) and includes a standard extension to ToolBook developed at UMTRI [*5,6*].

The database can be considered at four levels. Figure 10 shows a graphical view of the first three.

1. **Data screens**. Any screen display in VDM RoAD that has editable fields or other forms of user settings is called a data screen.
2. **Data sets.** A data set is the information you provide and can edit in a data screen, minus the screen itself. The data screen is a view of a data set as seen through the SGUI (the VDM RoAD graphical interface).
3. **Libraries.** A library is a collection of one or more data sets, plus the information needed to provide a view in the user interface. The next figure shows the contents of a library: multiple data sets, plus a graphical view of one data set at a time.
4. **The VDM RoAD database.** VDM RoAD includes about 50 libraries.

Individual data sets in the library



Data Screen:
A view of one data set though the graphical user interface

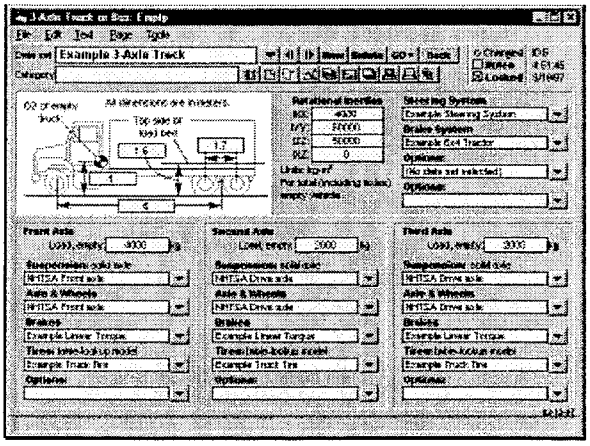


Figure 10. Contents of a VDM RoAD library.

Data Screens

Figure 11 shows an example data screen. Each data screen has three kinds of elements with which the user interacts.

1. **Yellow fields.** These contain data that can be edited directly. For example, to change wheelbase, find the yellow field with the current wheelbase value (3), click on the field, and change the value using the mouse and keyboard.
2. **Buttons.** All of the library screens include buttons at the top to quickly navigate through the data sets in the library and to go to other libraries and programs in VDM RoAD (see the buttons near (2)).
3. **Pull-down menus.** Some of the buttons are marked with a triangle [▼], indicating that pressing them with the left mouse button brings up a pull-down menu.

The yellow field in the upper-left corner of the screen is the title of the data set: **AASHTO 3-Axle Tractor** (1). (The title is simply text chosen by the user to identify this data set in the library. It has no significance to the simulation.)

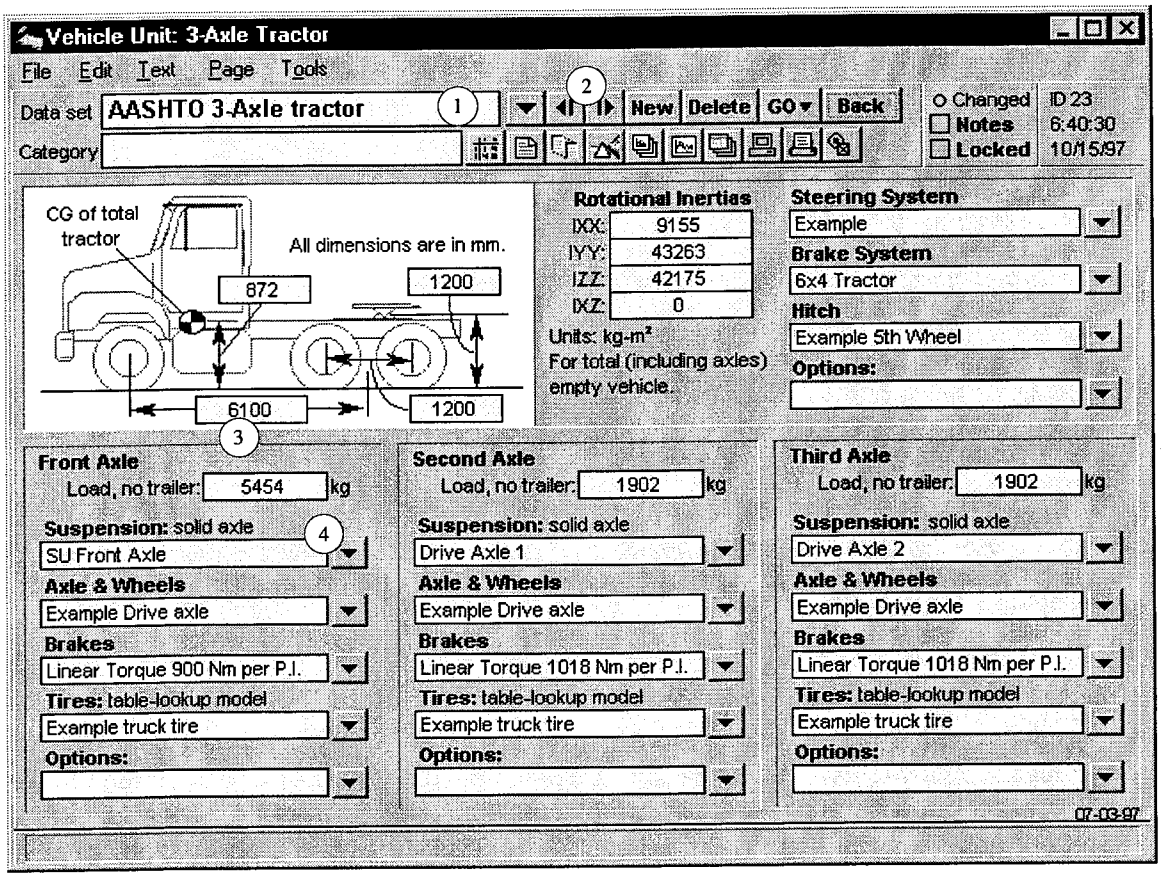


Figure 11. Example data screen.

The Simulation Solver Programs

VDM RoAD contains programs that solve the equations of motion for vehicle models, predicting motions, forces, and other variables. The solver programs are so-called console applications. Each behaves as a terminal console, with no user interface other than the display of text and the acceptance of keyboard entries. Figure 12 shows

that they have the same appearance as a plain DOS text program. However, the solvers are technically 32-bit Windows programs.

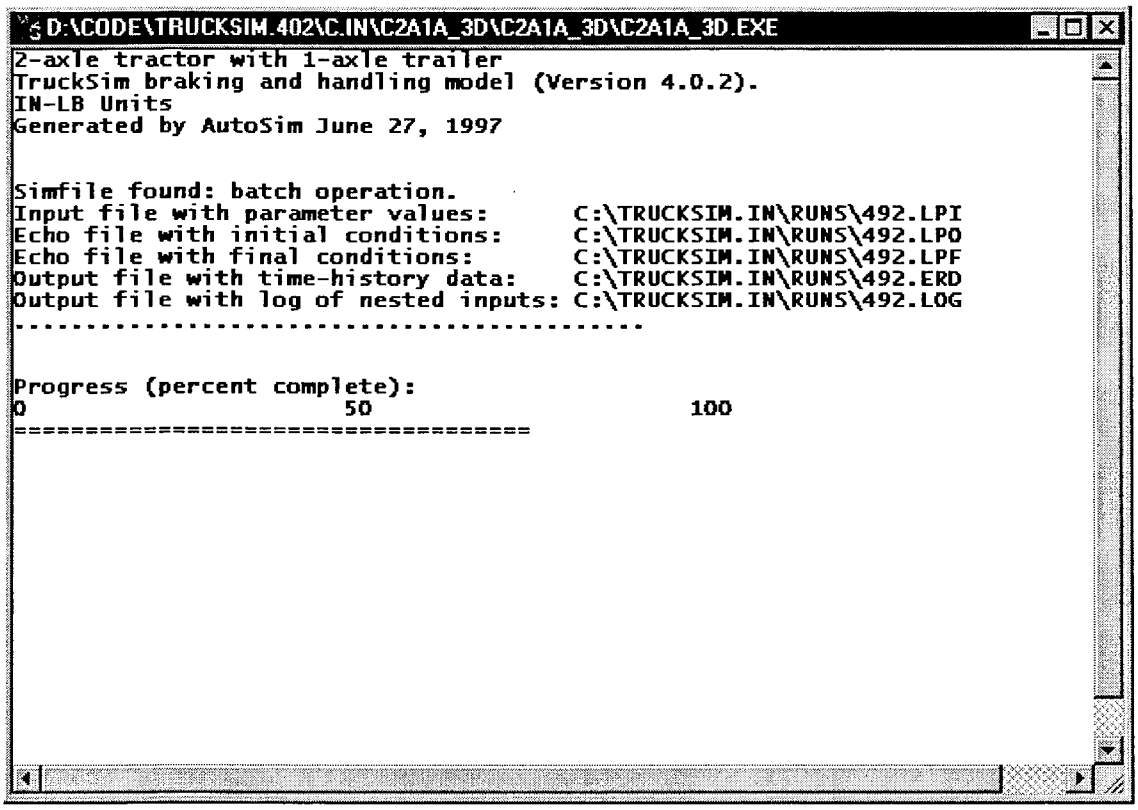


Figure 12. Screen display when solver program is running.

The solver programs contain equations of motion for the vehicle model in the form or ordinary differential equations. The equations are far too complex to solve in closed-form, so numerical integration is used. The source code for each simulation program is generated using the AutoSim commercial multibody program [*7*]. All of the equations related to the kinematics and dynamics of rigid bodies are derived and assembled automatically. However, equations for the tires, spring, driver model, and road geometry are contained in hand-written subroutines that are linked with the AutoSim-generated code. This approach allows highly complex mechanical systems to be simulated with high confidence that most of the computer source code is free of common human errors. Also, the equations generated by AutoSim have been shown to be highly efficient, generally running faster than equations generated by other means [*8*].

When a simulation program runs, it creates summary files that list each parameter value. One of these files is created before the run (LPO), and the other is created at the end of the run (LPF). Both contain all parameter values. In addition, the LPO file contains the initial conditions for the state variables in the simulation. The information in the LPO file is sufficient to exactly repeat a run. The LPF file is nearly identical, except

that instead of initial values, it contains final values of the state variables. By modifying the start and stop times, an existing run can be continued, possibly using a different kind of simulation program.

The main purpose of each simulation program is to calculate time histories of variables of interest. Those time histories are stored in a binary data file with the extension BIN. The BIN files contain numerical data organized by channel number and sample number, similar to test data recorded on a multitrack recorder. A companion file, with extension ERD, describes the layout of the BIN file and contains labeling information for each variable. It also contains the information that would normally be put into a log sheet summarizing the data, including text needed for preparing graphical plots of the data. By convention, ERD and BIN file pairs are simply called ERD files. The name ERD is used because the format was created by the Engineering Research Division at UMTRI, where it has been used since the early 1980s.

Data processing programs for ERD files obtain most of the information needed from the file itself. For example, the high level of automation in the animator and plotter exists because both were designed to work with ERD files.

VDM RoAD can also be made to produce simple text output files, for export to spreadsheet programs and other analysis software.

The Animator

VDM RoAD includes a program for animating wire-frame figures to visualize vehicle motions. The animation is accomplished by drawing images similar to what would be seen with a video camera and updating the images many times per second to show motion.

The view depends on where the camera is located. It is also determined by how the camera is aimed. Figure 13 shows the basic geometry and the relationships between the camera point, a look point, the 3D system being animated, and the 2D image that is recorded.

The animator program reads two kinds of input files (see Figure 14). Motion variables are read from an ERD file, created by the simulation programs whenever a run is made. Other information—such as program settings, definitions of parts, and shape information— are described with keyword-based text files (with extension PAR). The PAR files transfer user settings from the SGUI to the animator.

The animator program in VDM RoAD is also used in other software packages and is updated often. The most recent version can be downloaded via the Internet from the web site: **`http://www.trucksim.com/animator.html`**.

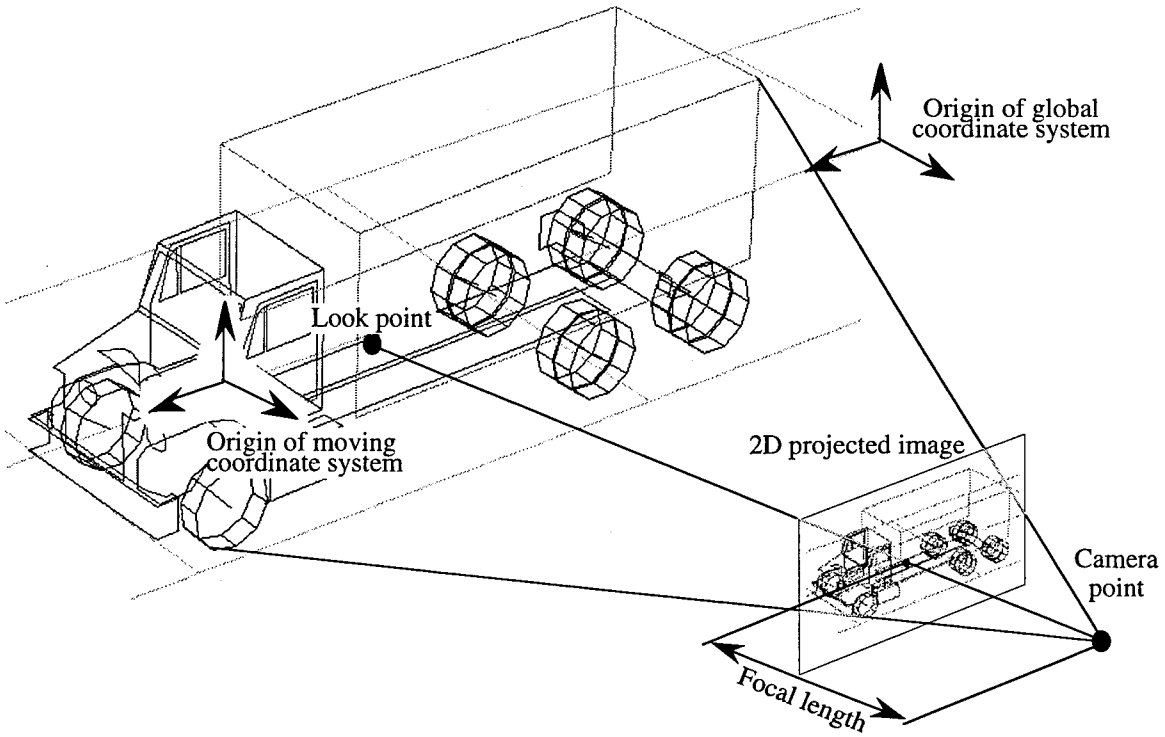


Figure 13. Geometry of the camera point and the look point.

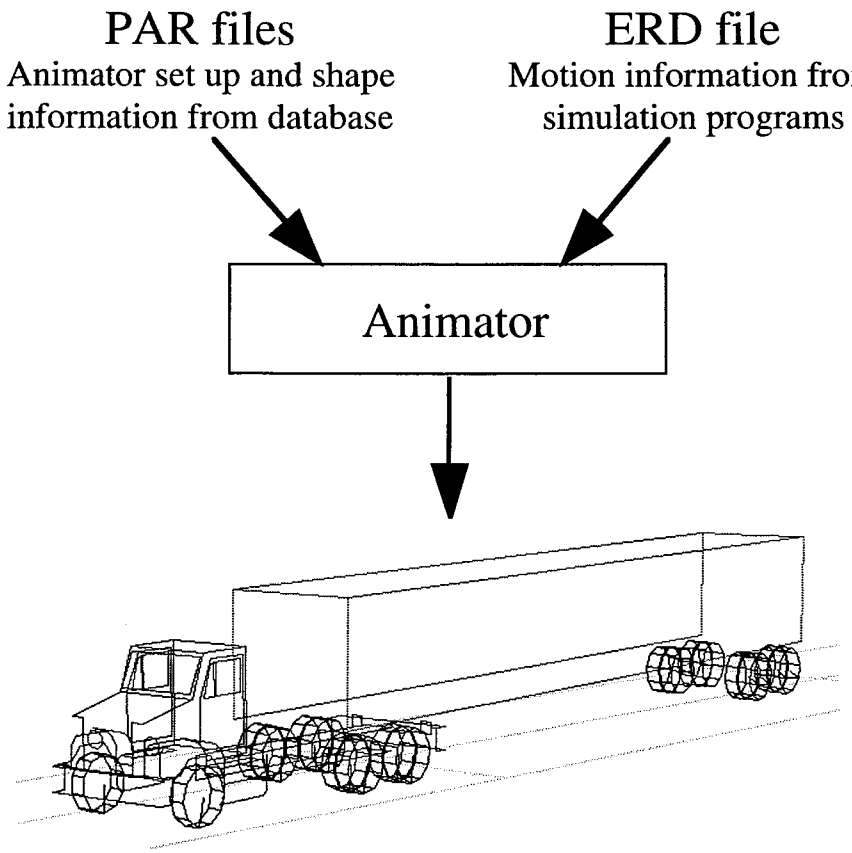


Figure 14. Animator input files.

The Plotter

Plots of the VDM RoAD simulation results are viewed with a program called Windows Engineering Plotter (WinEP). WinEP is a versatile tool that can be used to plot any two variables against each other. It can also overlay data from the same file or different files.

WinEP has a workspace defined by a main window with a menu bar. The main window contains plot windows, each showing plots made with a single set of X-Y axes. Figure 15 shows the main WinEP window with three example plot windows.

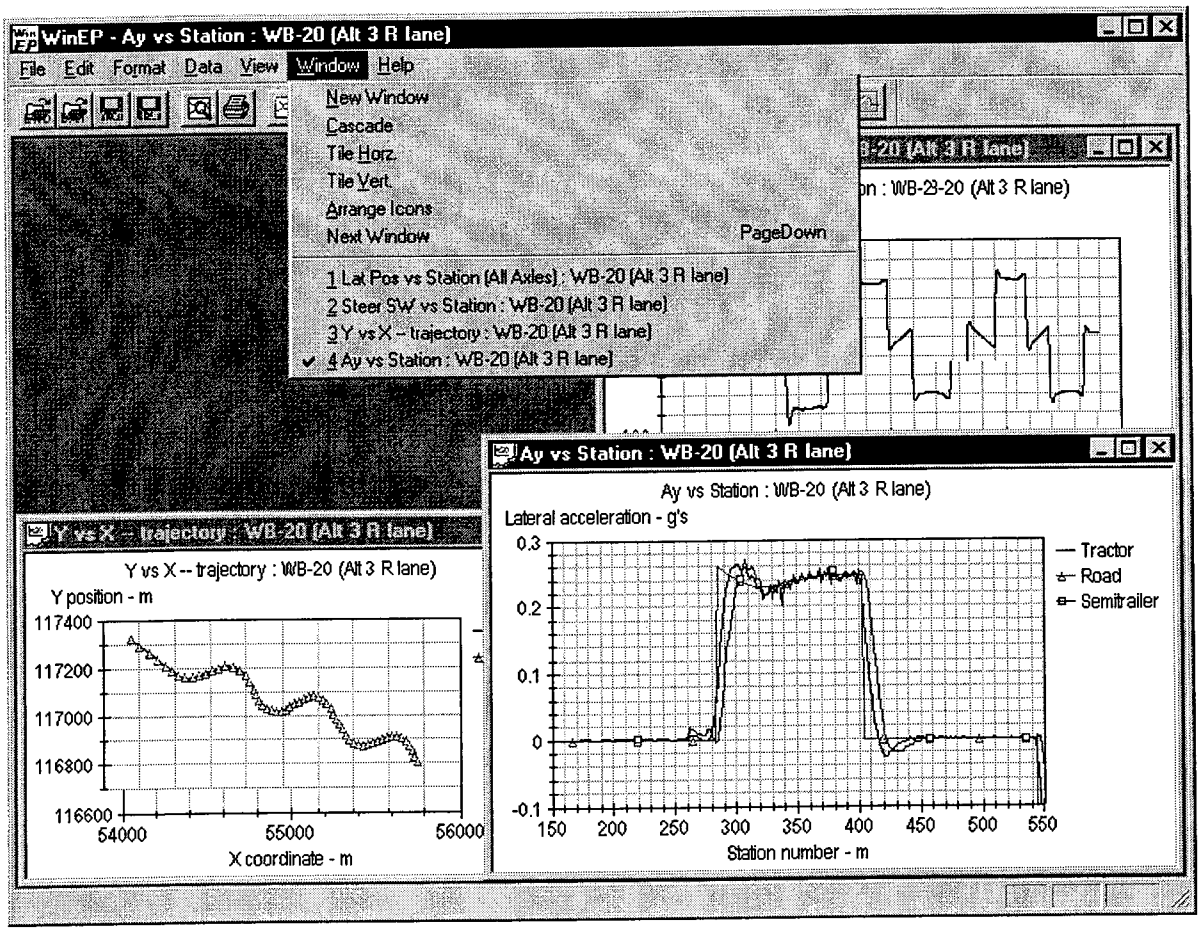


Figure 15. The WinEP workspace.

Each plot window contains a graphical representation of one or more X-Y data sets. An X-Y data set is a series of X and Y values obtained from a data file. The X-Y data sets can come from the same file or from different files. The X values in each data set do not have to be the same, and the data sets do not have to contain the same number of points.

WinEP is used in other software packages and is updated often. The most recent version can be downloaded via the Internet from the web site: **`http://www.trucksim.com/winep.html`**.

Batch Control

The VDM RoAD database includes vehicle descriptions, target paths (lateral position as a function of station number), target speeds (speed as a function of station number), and IHSDM data files with road geometry. The database also includes descriptions of runs, plots, and animations. For example, the **Runs** screen (see Figure 2 and Figure 3) shows a data set for a run, and the **Runs** library contains the data sets for numerous runs.

VDM RoAD also contains several data sets that include groups of runs and/or plot settings. For example, Figure 16 shows a screen used to make a batch of simulation runs. The user uses the **Add** and **Remove** buttons to create a list of runs in the lower-left part of the screen (under the heading **Data Sets to Run**). Each line in this list is the name of a data set from a **Runs** library. After the list is created, the user can update all runs with a single button click. This is convenient, for example, if the roadway design has been changed and a large number of vehicle responses are of interest for the new design.

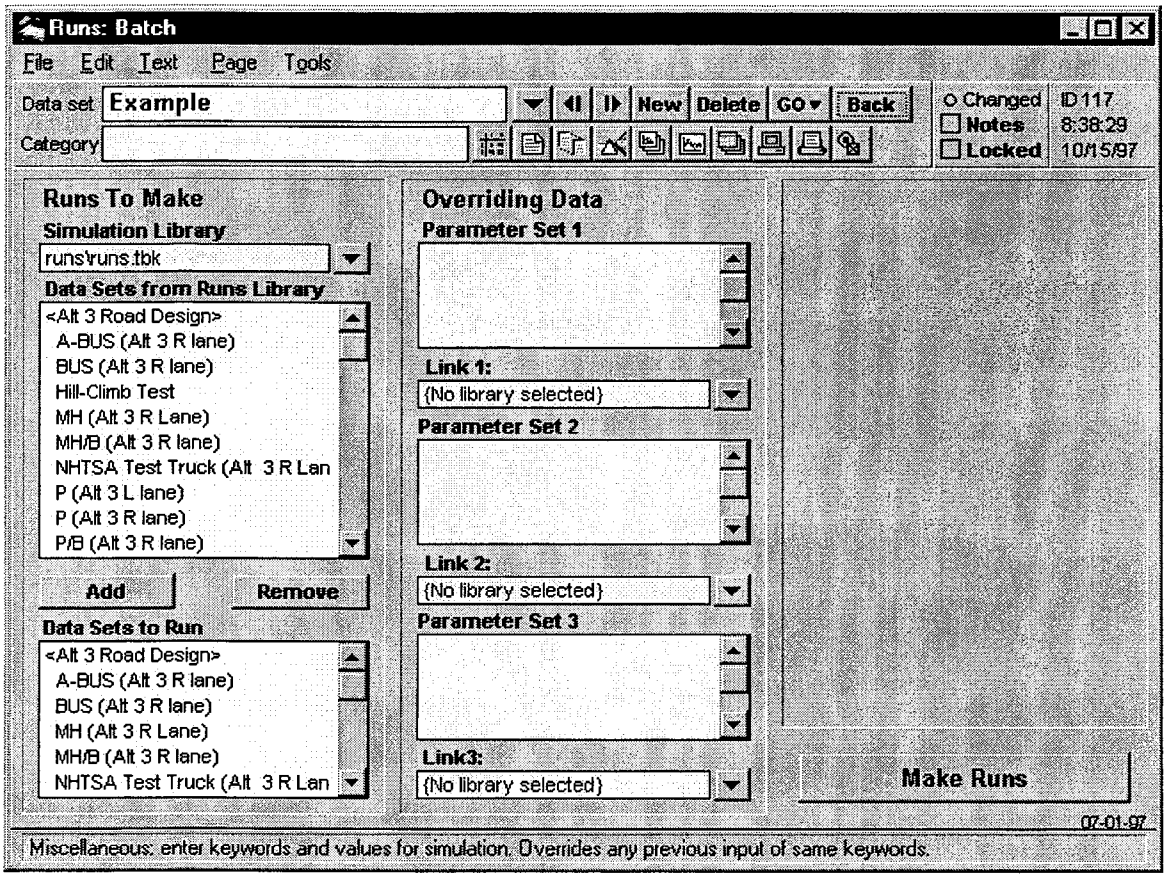


Figure 16. Batch run control.

Comparison of VDM RoAD and TruckSim Features

VDM RoAD uses mathematical models similar to those in the commercial programs TruckSim and CarSim. The models are based on research conducted over the past few decades at UMTRI [*9,10*]. The TruckSim and CarSim software packages were further

developed and commercialized by Mechanical Simulation Corporation (MSC), a private company in Ann Arbor, Michigan. MSC licenses, maintains, and supports TruckSim and CarSim.

TruckSim and VDM RoAD use the same graphical interface and database, the same animation program, and the same plotter. The vehicle models have the same input parameters, and the same equations are used to simulate vehicle dynamics. However, TruckSim is designed for mechanical engineers interested in studying vehicle dynamics and the effects of changes in vehicle design. On the other hand, VDM RoAD is designed for civil engineers to evaluate candidate road designs and to see the effect of changes in road design. Accordingly, the two software packages have some significant differences, as summarized in Table 1.

In order to make new runs with TruckSim or CarSim, the user must have a hardware "key" (called a DONGLE) that attaches to the parallel port of the PC. FHWA has been provided with two copies of TruckSim, along with two hardware keys.

All rights to VDM RoAD have been transferred to the government. The VDM RoAD software does not require a hardware key and can be distributed as the government chooses. The source code for VDM RoAD has been provided to FHWA.

Table 1. Comparison of TruckSim and VDM RoAD features.

	VDM RoAD	TruckSim
Vehicle Model Features		
Full nonlinear 3D equation sets	Yes	Yes
Full nonlinear suspension components	Yes	Yes
Nonlinear brakes with air dynamics and ABS	Yes	Yes
Full nonlinear tire model with 2D tables	Yes	Yes
Alternate support for STI tire model (1994 version)	Yes	No
Full 3D tire/road interface (slope + cross slope)	Yes	No
Number of truck models	4	6
Number of car models	1	0
Unit systems	metric	metric or English
Control and Road Inputs		
UMTRI driver model for following path	L vs. S	Y vs. X
Speed control	V vs. S	V vs. T
Open-loop steer control	No	Steer vs. T
Brake input	Pressure vs. T	Pressure vs. T
IHSDM interchange file	Yes	No
User-specified initial conditions	S, L	XYZ, angles
User-specified road friction	Yes	Yes
Simulation stopping variables	S, T, Roll, V	T, Roll, V
Output Variables (Available for Plotting)		
Vehicle X-Y-Z and yaw-pitch-roll for animation	Yes	Yes
Lateral accelerations	Vehicle, road	Vehicle
Tire forces and moments	Yes	Yes
Slope and cross slope under wheels	Yes	No
S, L coordinates of wheels	Yes	No
Road-based points-of-view for animator	Yes	No
Tire kinematics: lateral slip, inclination, etc.	No	Yes
Suspension spring and damper forces and deflections	No	Yes

3. INTEGRATION WITH ROAD DESIGN DATA

This section provides an overview of the road geometry used in the VDM RoAD models, and then describes how the road design data are integrated with the vehicle dynamics models.

The road design data are used to perform several functions in the VDM RoAD design:

1. to provide a continuous 3D surface that supports the vehicle and interacts with the tires,
2. to provide a horizontal path as a reference for the closed-loop steering model, and
3. to determine the location and orientation of the vehicle at the start of a simulation run. (The location and orientation are part of the vehicle "initial conditions.")

Using road design data together with a vehicle dynamics model requires the information in the roadway coordinate system to be compatible with the vehicle coordinate system. The following subsections describe the roadway and vehicle coordinate systems, and the general methods used to transform information between them. After the roadway coordinate system has been described, the section concludes by describing how the above three functions are accomplished.

Coordinate Systems

The describing dynamical equations for a vehicle are solved by the simulation programs in VDM RoAD to provide coordinates of critical points in the vehicle based on a global X-Y-Z coordinate system. The road design data from the IHSDM data file is also tied to a global X-Y-Z coordinate system. The global system is needed by the underlying CAD system to perform calculations and to prepare graphic views of the design.

The location of an arbitrary point P in 3D space requires a coordinate system with three independent coordinates. For the X-Y-Z system, the three coordinates are X, Y, and Z—each defined as the distance from the origin along a line parallel with the named axis. To locate point P, one would:

1. start at the origin and then go X meters along the X axis,
2. then go Y meters parallel with the Y axis, and, finally,
3. go Z meters up, parallel with the Z axis.

The global X-Y-Z coordinate system is theoretically sufficient for locating any point of interest in the road and any point of interest in the vehicle at a specific instant of time. However, it is desirable to locate the vehicle using station number (S) and lateral distance (L) from the design centerline, rather than global X and Y coordinates.

The data in the IHSDM file define a continuous, curved reference design line (typically the centerline) in 3D space. The 2D horizontal geometry is defined by projecting the 3D line onto the global X-Y plane, as shown in Figure 17. Station number is defined as the distance along the 2D projection.

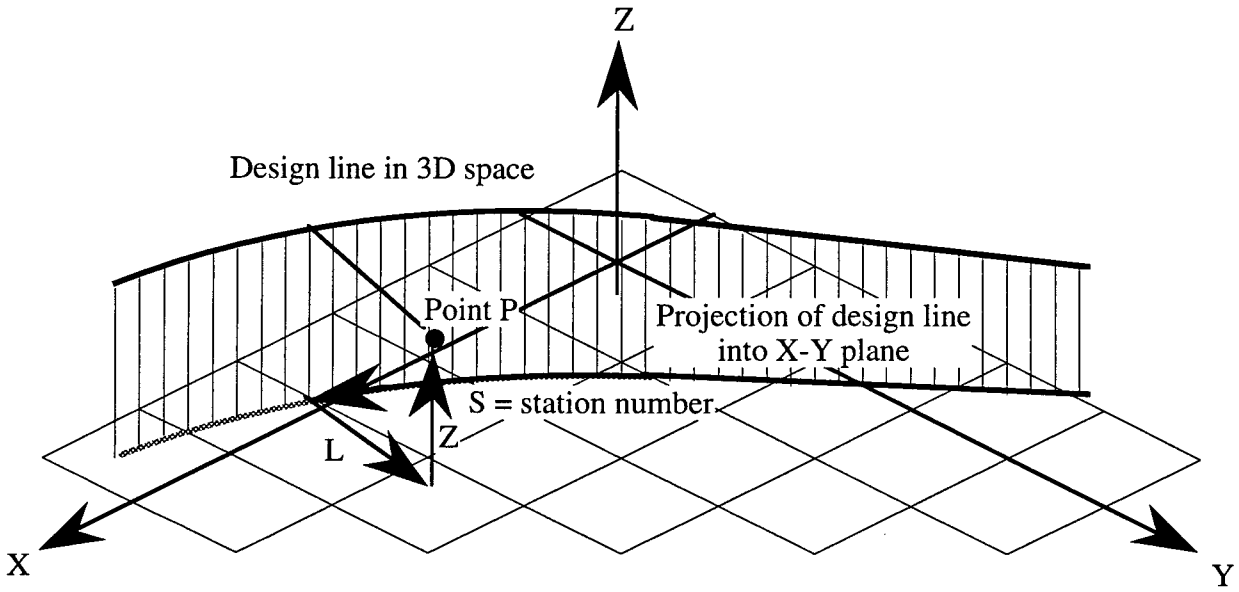


Figure 17. The S-L-Z coordinate system.

The road coordinate system in VDM RoAD involves three coordinates named S, L, and Z. The Z coordinate is the same as in the X-Y-Z system. The other coordinates, S and L, are based on the design centerline. To locate point P in the road coordinate system, one would:

1. start on the projection of the road design line into the X-Y plane at station S=0 and then travel along the projection of the design line S meters,
2. then go laterally L meters, along a line in the X-Y plane that is perpendicular to the projection of the design line, and finally,
3. go up Z meters, parallel with the Z axis.

The right-hand rule requires that L be positive for positions to the right of the centerline when facing "upstream" (in the direction of decreasing S). If facing in the direction of increasing S, then points to the left of the centerline are positive and points to the right are negative.

The sign-convention for L defines a "right-handed coordinate system" when positive Z is up. Only right-handed coordinate systems are used in complex commercial 3D software packages. Thus, a right-handed system was defined for VDM RoAD.

Coordinate System Transformations

The Z coordinates from the X-Y-Z and S-L-Z systems are the same. Therefore, transformations between the two systems involve only the two-dimensional X-Y and S-L systems.

The process of transforming S-L coordinates into X-Y values is direct. For any pair of S-L values, there is a single pair of X-Y coordinates. Figure 18 shows the geometry for an arbitrary point (X, Y), the centerline, and a design point on the centerline (X_i, Y_i).

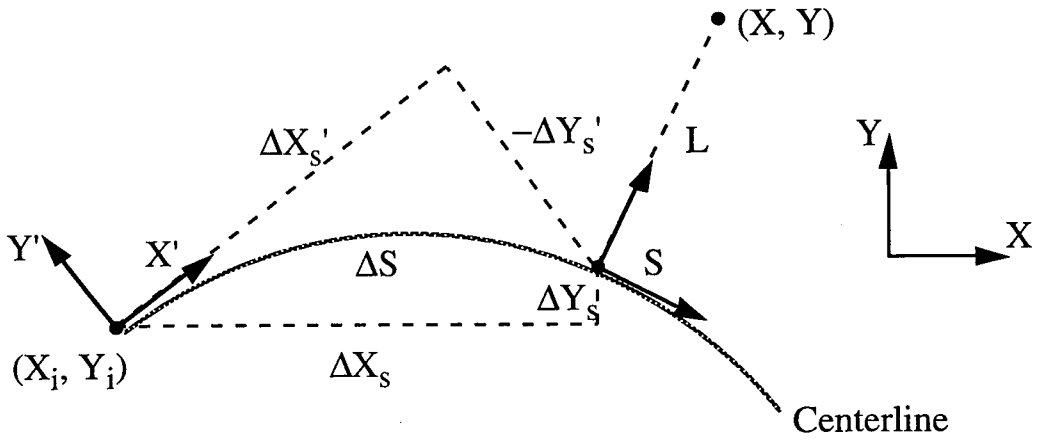


Figure 18. Computation of X-Y from S-L.

The process for computing X and Y is as follows:

1. Find the index i for the last design point preceding S. This is done using a table-lookup procedure.
2. Compute the S distance of the current point past the last design point. This change is shown in Figure 18 as ΔS.
3. Compute changes in X and Y in a rotated coordinate system where X is tangent to the centerline at the design point. These changes are shown as $\Delta X_s'$ and $\Delta Y_s'$ in Figure 18. The details of the calculation depend on whether the road centerline is (a) straight, (b) has a constant radius, or (c) is on a spiral.
4. Using the heading angle of the centerline at the design point, transform the quantities $\Delta X_s'$ and $\Delta Y_s'$ to obtain X and Y changes in the global coordinate system (ΔX_s and ΔY_s).
5. Add ΔX_s and ΔY_s to the coordinates of the design point, X_I and Y_i. This gives the X and Y coordinates at a point on the design centerline at S.
6. Determine the heading angle at S. (Different methods are used depending on whether the road is straight, on a constant-radius turn, or on a spiral.) Use the heading angle to determine changes in X and Y due to L.

7. Add the X and Y offsets (from step 6) to determine the X and Y coordinates for the point at S, L.

Additional details of the transformation are provided in Appendix H of the VDM RoAD User Manual [2].

Converting from X-Y coordinates to determine S-L values is not as direct as the above transformation. One complication is that multiple values of S-L can exist for a single point in X-Y space. For example, the center of a design curve can be equally well defined using any value of S along the curve, with the magnitude of the L value being equal to the radius.

The method is described in Appendix H of the user manual. It requires knowledge of the design point S_i that is associated with X and Y. Separate transforms are presented for tangent and constant-radius turns. The geometry has not yet been worked out for spirals.

A procedure is followed to compute ΔS and L. The calculated value of ΔS is then inspected, to see if the assumed design point was correct. For example, if the design point is located at the start of a curve covering 200 meters, the valid range of ΔS is 0 to 200. If the computed value of ΔS is greater than 200, then the calculated values of S and L are not correct because the point of interest is past the end of the curve. In this case, the procedure would be repeated using the next design point.

Applications of the Road Coordinate System

As noted at the start of this section, there are several applications of the transformations in VDM RoAD.

Tire/Road Interactions

The most essential application of the road geometry is to define the 3D ground surface under each wheel of the vehicle, such that the interactions between the ground and the tires can be computed. Figure 19 shows vectors that describe the four main actions on the vehicle generated by the tire: longitudinal force (F_X), lateral force (F_y), vertical force (F_Z), and aligning moment (M_z). The three forces apply at a point defined by the intersection of the wheel plane with the 3D road surface. This point, labeled W_c in the figure, has X and Y coordinates that are known approximately from the vehicle model. The Z coordinate is determined by the road design data.

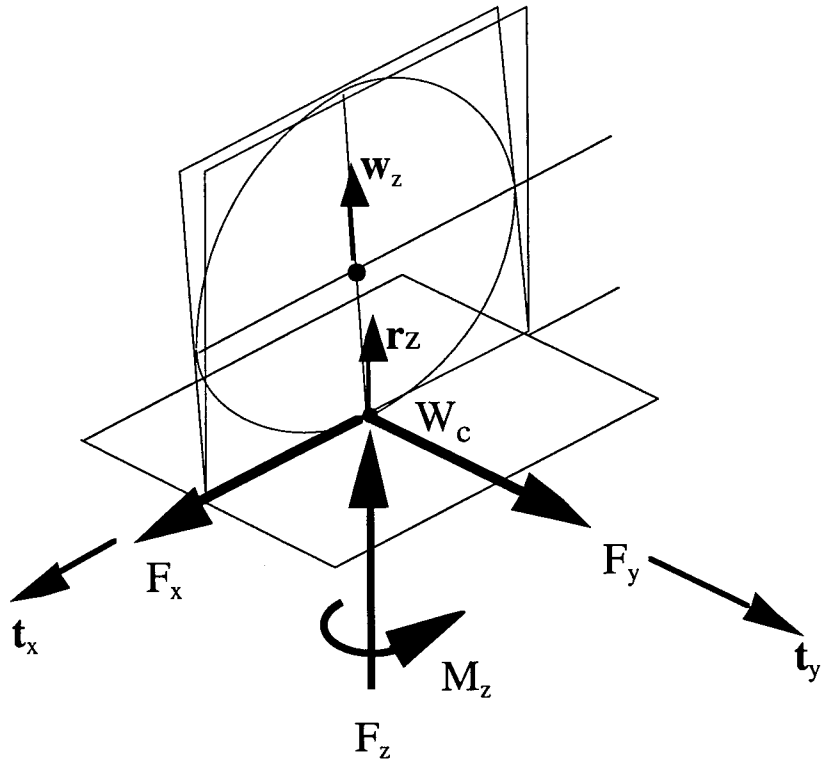


Figure 19. Directions of tire action vectors.

The road normal vector is shown in the figure and labeled $\mathbf{r}_z$. (The road normal is a vector whose direction is perpendicular to the road surface.) If the road is flat and level, $\mathbf{r}_z$ points straight up, in the direction opposite of the gravity vector. However, in general, it is tilted slightly due to vertical geometry and superelevation. The road normal is used in the vehicle dynamics models, together with the direction of the spin axis of the wheel, to define the vectors $\mathbf{t}_x$ and $\mathbf{t}_y$ that define the directions in which the tire longitudinal and lateral forces are applied.

In order to calculate the directions of the vectors, it is necessary to determine the road normal at each tire location (W_c). Starting with the X and Y coordinates of point W_c, the vehicle simulation programs in VDM RoAD compute Z and two slope values. The process is as follows:

1. Determine the S-L coordinates associated with the point by transforming the known X-Y coordinates.
2. Determine the Z coordinate of the design centerline at S, based on vertical geometry data. Also, determine the longitudinal slope: $\partial Z/\partial S$.
3. For the current station (S), calculate change in Z as a function of L due to design superelevation. Also, determine the lateral slope: $\partial Z/\partial L$.
4. Add the superelevation effect (step 3) to the centerline elevation (step 2) to obtain the total height of the road surface at the wheel contact point.

5. Transform the two slope values (∂Z/∂S and ∂Z/∂L) to slopes with respect to the global X and Y directions (∂Z/∂X and ∂Z/∂Y). Use the sine and cosine of the road-heading angle to accomplish this.

The complete details for computing Z and the two slope quantities are presented in Appendix H of the VDM RoAD Users Manual. The application of these quantities to the vehicle model is described in Appendix G.

Interactions With the Closed-Loop Steer Controller

In order to simulate the driving of a vehicle over a 3D road design, the vehicle models in VDM RoAD include a closed-loop steering controller. Figure 20 shows a simple flow-chart of the controller logic.

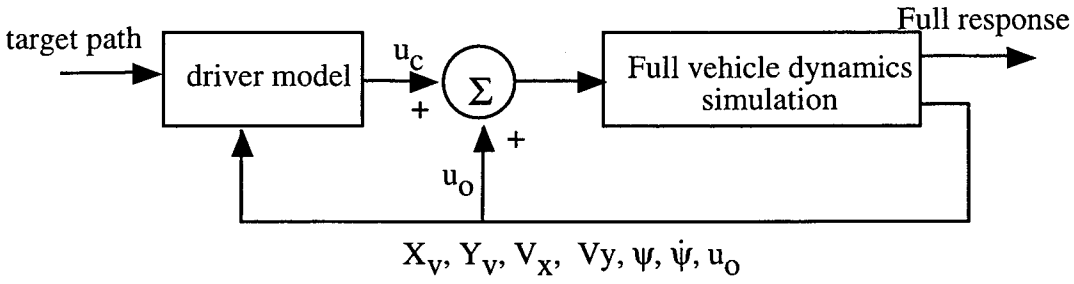


Figure 20. Closed-loop steer controller.

The driver model takes as inputs a target path and some feedback variables from the full vehicle model. The controller works by looking ahead by some amount of time and determining the steering wheel angle (shown in the figure as u_c) that will cause the vehicle path to best match the target path over the preview interval. The steering from the driver is added to a steering due to other factors (mechanical kinematic and compliance properties of the suspension), shown in the figure as u_o.

The driver model includes parameters, control logic, and even a simplified vehicle dynamics model. The target path is defined with a table of L versus S values, as shown for an example lane change in Figure 21. In the figure, the input path would start at the design centerline, changing to a point 3.35 m left of the centerline after station S=135 m.

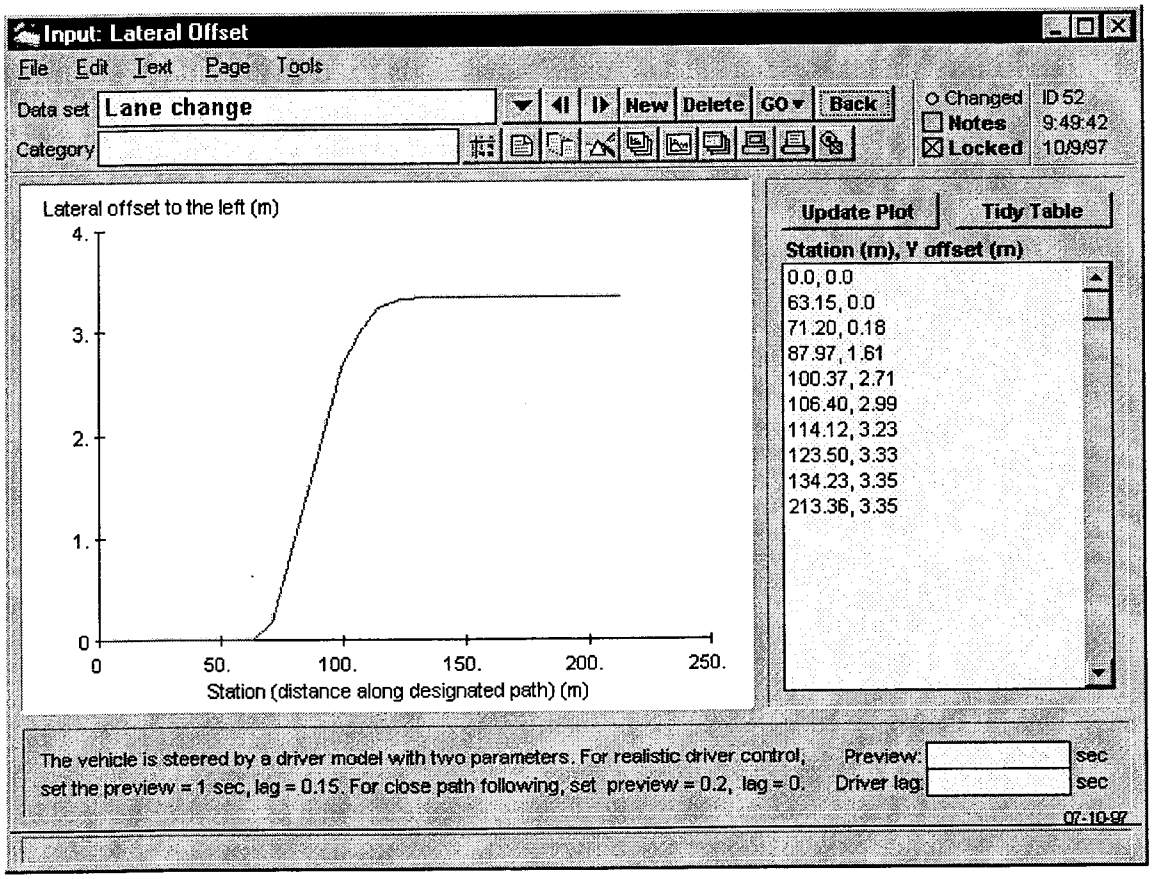


Figure 21. Target path input.

The driver model must determine the lateral position of the target path, relative to a coordinate system based on the moving vehicle. Figure 22 illustrates the geometry.

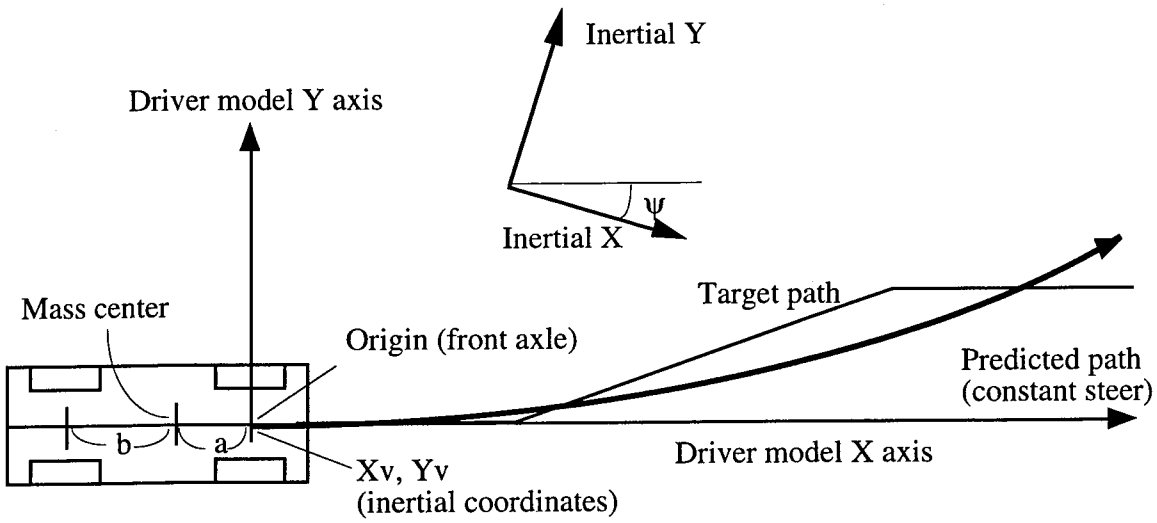


Figure 22. Coordinate system of driver model.

The driver model algorithm makes the following coordinate system transformations:

1. The global coordinates of a reference point (X_V, Y_V) are converted to the roadway S-L system to determine the station number for the reference point.
2. Using the current vehicle speed and direction (increasing station or decreasing station), station numbers are computed for 10 equally spaced target points lying ahead of the vehicle. The distance to the 10th target point is the preview time (sec) multiplied by the current vehicle speed (m/sec).
3. At each of the 10 target points, the lateral coordinate of the target path (see Figure 21) is determined by table lookup.
4. The S-L coordinates for the 10 target points are transformed to the inertial X-Y coordinate system.
5. The lateral location in the driver model coordinate system is calculated for each target point by first getting the inertial X and Y coordinates of the path as functions of the station at the target location (S_{targ}), and then applying the transformation

$$Y_{targ} = [Y(S_{targ}) - Y_V] \cos(\psi) - [X(S_{targ}) - X_V] \sin(\psi)$$

where ψ is the vehicle heading angle.

The above strategy is valid for any location of the vehicle where a station can be computed. At zero speed, the look-ahead is set to a small distance to avoid numerical problems. Complete details of the control algorithm are described in Appendix I of the VDM RoAD Users Manual.

Initialization of the Vehicle Position

At the start of each simulation run, the vehicle position and orientation are set to match the road geometry, initial station number, target speed, and target lateral position.

The user of VDM RoAD specifies a starting and stopping station number for each simulation run. For example, in Figure 2 on page 4, the run starts at station 0 and stops at station 1900. The starting and stopping station numbers are used for three purposes in VDM RoAD:

6. The starting station number, designated S_o, is used to locate the vehicle at the start of the run.
7. The stopping station number is used as a criterion for stopping the run.
8. The starting and stopping station numbers are compared to determine the direction the vehicle is traveling (increasing station or decreasing station).

More specifically, the initial conditions of the vehicle are set as follows:

- The vehicle reference point (center of front axle) is located at the starting station number S_o specified on the **Runs** screen.
- The vehicle reference point is located at the lateral position L specified as the target location at the given starting station: $L(S_o)$.

- The heading of the vehicle is set to match the heading of the road at S_o when vehicle is traveling in the direction of increasing station. When traveling in the opposite direction the heading is set opposite that of the road.
- The pitch angle of the vehicle is set to match the longitudinal slope of the road at S_o. When traveling in the opposite direction, the negative slope is used.
- The roll angle of the vehicle is set to match the superelevation of the road at S_o and $L(S_o)$. When traveling in the opposite direction the negative superelevation is used.
- The tire deflections are set to provide the static loads that would be expected on a flat, level surface at zero speed.
- Suspension deflections are set to provide the static spring forces that would be expected on a flat, level surface at zero speed.
- Forward vehicle speed is set to match the user-specified input: $V(S_o)$.

The tire and suspension deflections are generally not exactly equal to the equilibrium values, although they are close. For the car model, aerodynamic forces and moments are neglected. For all models, a number of secondary effects are neglected. For example, load transfer is neglected between wheels due to small pitch and roll angles. Consequently, the first second or so of the simulation usually includes some bouncing, pitching, and rolling of the vehicle as it settles into an equilibrium condition on the 3D road surface in the presence of aerodynamic effects.

4. INTEGRATION WITH A DRIVER PERFORMANCE MODULE

A major part of the planned IHSDM system is a driver performance module (DPM). The DPM interacts with vehicle dynamics simulations from VDM RoAD (or an alternative vehicle dynamics module) to predict the motions of a driver/vehicle system on the road. This section describes how the DPM can be integrated with VDM RoAD.

Overview of Man-Machine Simulation

Models of man-machine interactions can involve multiple levels of human behavior. For example, Jens Rasmussen provides a framework for providing three levels of abstraction involving human control of machines [*11*]. The three levels are called skills, rules, and knowledge. Figure 23 shows how these levels of performance can be related to the modeling of driver-vehicle interactions.

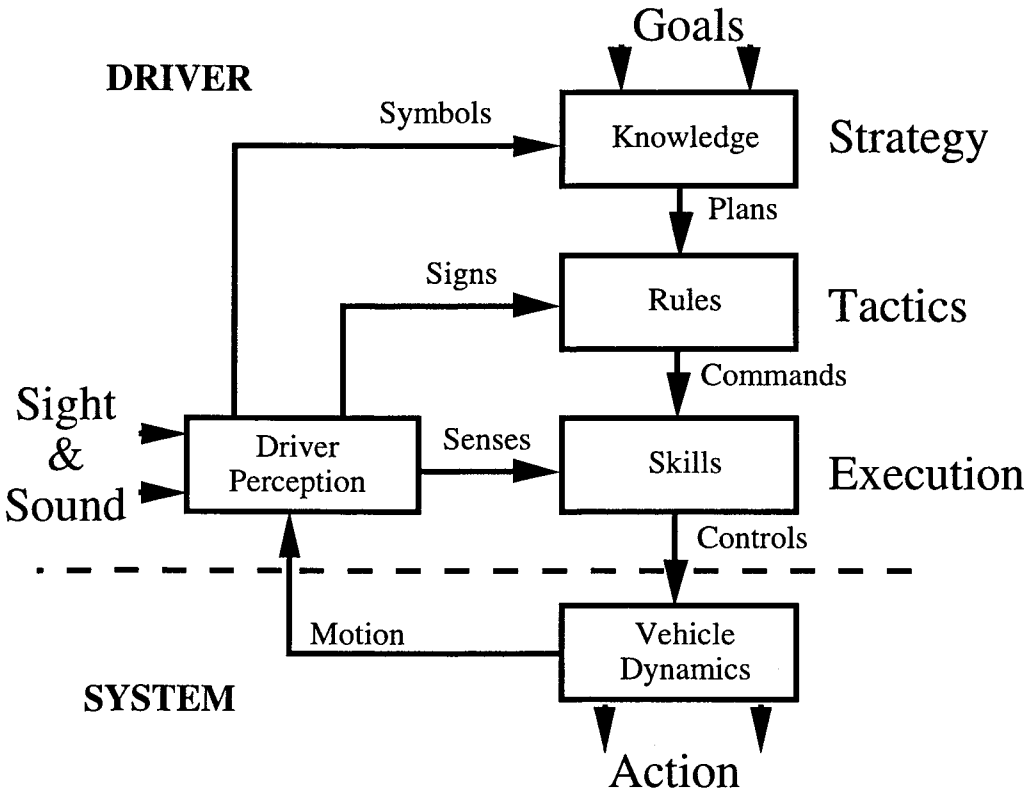


Figure 23. Driver control behavior.

The "big picture" of man-machine interaction as described by Rasmussen covers extremely abstract notions, such as the analysis of unfamiliar situations and development of general plans or strategies, based on the knowledge of the human. The next level is

less abstract. It involves tactical decisions based on rules developed from past experience. The outcome of the knowledge and rule-based behavior are commands. In the context of the driver of a vehicle, the commands are a target speed and lateral position of the vehicle on the roadway. The third level of behavior involves the driver controlling the vehicle through the steering wheel, throttle, and brakes. The objective of the driver is to use previously learned skills to execute the commands.

Integration of DPM and VDM

The DPM is presently in the early stages of development, and details of its operation have not been finalized. However, it is probably safe to assume that at least the two inner-loops shown in Figure 23 will be included in the IHSDM (simulation of driver rules for choosing paths and speed, and simulation of driver steering and speed control).

There are several methods by which the DPM and VDM modules can be integrated. Three possibilities are mentioned below.

1. The DPM and VDM programs can be merged into a single program that simulates both the vehicle dynamics and the driver control behavior.
2. The DPM and VDM programs can be modified to run concurrently, exchanging information as they run.
3. The DPM and VDM programs can be run sequentially. The DPM would be used to generate target paths and speed, and then the VDM program would be run to generate the vehicle-specific response to those commands.

Of these three methods, the third is recommended. Before describing how the DPM and VDM would be run sequentially, the rationale will be presented for rejecting the first two approaches.

Problems with Running DPM and VDM Simultaneously

Merging the DPM and VDM parts of IHSDM would involve taking the computer source code (C, Fortran, etc.) for the two modules and combining the code into one single program module. Although this approach is conceptually simple, it is not practical. The VDM RoAD simulation programs are large, complex programs that are designed as "stand-alone" programs. They are not designed to be merged with other software and there is no documentation that describes how this would be done. Considerable expertise would be needed by the programmers to understand their design and modify them to work together with the DPM.

It should also be noted that the vehicle simulation in VDM RoAD is not performed by a single program. VDM RoAD includes five separate vehicle simulation programs each customized with equations of motion for a specific class of vehicle (cars and four configurations of heavy trucks). At least five separate VDM/DPM programs would have to be constructed. (Of course, it is also theoretically possible to merge the five separate VDM programs and then merge that program with the DPM code. This possibility is discounted because it involves even more work and requires even more expertise.)

Modifying the VDM and DPM programs to run concurrently and exchange information is more feasible, but is still not recommended. There are at least two problems. One is that considerable expertise is still needed to modify the programs to properly exchange information. The programmers would have to master the design of the existing programs before they could modify them. The second problem involves efficiency. When multiple programs are run concurrently, there can be a great deal of overhead and inefficiency introduced, resulting in long run times.

UMTRI researchers have experience in how software can slow down when several simulation programs are made to run concurrently. A software package called ArcSim was developed to showcase simulation technologies developed under the U.S. Army Automotive Research Center (ARC) headquartered at the University of Michigan (see the web site: **http://arc.engin.umich.edu/**). ArcSim includes simulations of a military tractor-semitrailer with a mathematical model similar to the ones in VDM RoAD. The ArcSim program was modified and made to run concurrently with a separate simulation program, integrated using the commercial simulation program SimuLink (SimuLink is sold by The MathWorks, Inc., as an add-on to its MATLAB package). We found that two programs that both ran quickly by themselves were slowed down considerably when they were integrated. A run that would take less than a minute for either program by itself took hours when the programs were connected.

The slowdown was due partly to different time scales associated with the models. However, the more significant problem was that the interprocess communication was extremely inefficient. The problems of interprocess communication are, in our view, solvable. However, the amount of effort needed to solve the problem is not known. The problem of having different time scales also applies to the one of integrating VDM and DPM. The vehicle models include the high-frequency dynamics of subsystems that require small integration time steps, on the order of 0.002 sec. Removing the high-frequency dynamics reduces the accuracy of the simulation and is not easily accomplished. The DPM does not require such a small time step. Values of 0.01 to 0.1 sec are more typical.

Running DPM and VDM Sequentially

In viewing the control flow chart in Figure 23, consider the computation requirements for the three loops. The outer loop (knowledge) is so abstract it might be beyond the scope of DPM. Abstract thinking does not involve rapid coupling with vehicle dynamics, because the thinking process generally covers a time scale involving minutes or hours. The intermediate loop (rules) is probably the main part of the DPM. Taking into account traffic conditions, perceived road geometry, and the current speed and location of the driver's vehicle, the driver model generates commands in the form of a target path and target speed. The time scale involves seconds. The inner loop (skills) involves the close coupling of the driver control and the vehicle response. Given a target path and target speed, this level of control determines how the driver controls the throttle, brakes, and steering wheel to achieve the targets. This time scale covers tenths of seconds.

Given that only the inner loop (skills) involves a short time scale (high frequencies), it is possible to separate the driver control into two parts as shown in Figure 24. In this

figure, the DPM is the part of the simulation that produces commands: the target path and target speed. The VDM RoAD software includes the skill controller algorithms for generating steering wheel angle to cause the vehicle to follow the target path and the drive torque to cause the vehicle to maintain the target speed.

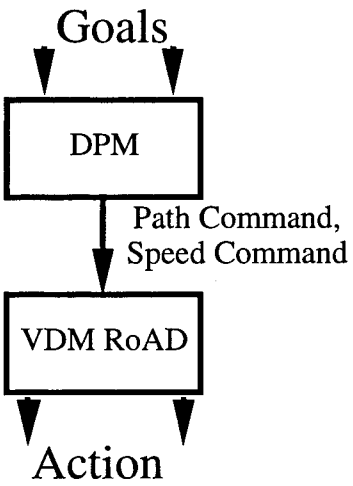


Figure 24. Simplified view of driver control.

The DPM/VDM system shown in Figure 24 would function in two steps:

1. The DPM module would take as inputs the road geometry, driver parameters, traffic conditions, and possibly a small number of vehicle parameters. (Vehicle parameters might not even be needed.) As output it would produce the target path (lateral position as a function of station number) and target speed (also as a function of station number).

2. VDM RoAD takes the target speed and lateral position as inputs and generates the steering wheel angle and drive torque to follow them, taking into account the full dynamic response of the vehicle.

In this design, the second part (VDM RoAD) is already complete. The first part (DPM) is being developed.

The rationale for this modeling approach is that the driver behavior involving knowledge and rules does not depend on details of the vehicle dynamics. It is assumed that when a driver decides what path to take, it is without regard to details of vehicle behavior. In planning a target path or speed, the assumption is that the driver will "do whatever it takes" to control the vehicle to hit the target. If the vehicle is sluggish, the controller in VDM RoAD will generate larger steering wheel angles. If the vehicle is responsive, the controller in VDM RoAD will generate less control. The DPM can perform all of the planning without concern for the details. VDM RoAD will then "do whatever it takes" to execute the plans.

Of course, in extreme cases, the vehicle will crash. When the controller tries to follow a path that is beyond the physical capabilities of the vehicle and road, an accident occurs

in the form of a rollover or of the vehicle skidding off of the road. In these cases, the simulated driver behavior will be wrong, pure and simple. However, this limit in accuracy is not necessarily a limit in the usefulness of the software. The basic objective is to identify potential problems involving road design, vehicle type, driver behavior, and signing. If the simulation shows a large amount of corrective steering, or tire loads reaching zero, then a problem has been identified and the software has provided useful information.

The details of how a driver and vehicle interact after the problem occurs is not of interest if an alternative design can be developed.

5. CONCLUSIONS AND RECOMMENDATIONS

This section presents the main conclusions drawn from the project and presents specific recommendations for the continued development of the IHSDM.

VDM RoAD Software

The main objective of this project was to select among existing vehicle dynamics simulation programs and link them through a common database to commercial roadway CAD programs. The existing TruckSim and AutoSim technologies were selected and extended for this project. The connection to roadway CAD packages is made through a standard IHSDM interchange file that is created as an output by CAD packages such as GEOPAK and read as an input by VDM RoAD.

The VDM RoAD provides an advanced simulation of vehicle dynamics that works with the 3D road design data. In just a few minutes, an engineer can simulate the behavior of a vehicle driving over several kilometers of a new roadway design. Results are viewed immediately. Vehicle motions can be viewed with wire-frame animation.

The software can be used by engineers who are not experts in simulation or even vehicle dynamics. This contrasts with older simulation packages where considerable expertise was needed in the fields of vehicle dynamics and numerical analysis. Further, the time needed to become proficient with simulation software has always been so lengthy that only the most determined engineers would become productive.

The software runs on Intel PCs equipped with Windows 95 or Windows NT. With Pentium Pro or Pentium II machines, the simulations run faster than real time.

The new software is almost ideal for simulating what would happen if a particular vehicle is operated on a particular road with a given input path (lane position as a function of station number) and speed (also specified as a function of station number). We recommend that the software be used for this purpose.

The UNIX Platform

When this project started in late 1993 the vehicle models and supporting programs existed only on the Windows platform. Yet, most States with road design CAD systems were using UNIX. As the project developed, one of the contract modifications included a task of porting the software from Windows to UNIX. A partially functional version of VDM RoAD exists on UNIX:

- The simulation solver programs are generally platform independent. The code is written in Fortran 77 and runs on any machine with a suitable compiler. Most of the code also exists in C (the exception is the interface with the IHSDM

interchange files). There were no problems generating executable binary UNIX files.

- The plotter and animator are C programs that make use of the graphics and user interface libraries of specific operating systems. The Windows versions make use of well-developed libraries and development tools that only exist for Windows. The UNIX versions are functional but would require considerably more development effort to reach the same level of utility as the Windows versions. Performance of the animator was disappointing—it runs slower on a workstation than the Windows version on a low-end PC.
- The graphical user interface on Windows is programmed in ToolBook [*4*]. A similar product for UNIX exists that is called MetaCard. However, we found that our productivity with MetaCard was much less than with ToolBook. We were never able to program the same level of functionality in the UNIX version of the graphic interface as was possible in the Windows version. We are not sure it is even possible.

Before the project concluded, FHWA changed the platform of choice for IHSDM from UNIX to Windows/NT.

We recommend that all UNIX products developed in this program be abandoned.

If there is a need in the future to run the vehicle dynamics simulations under UNIX, the source code for the vehicle models can be easily compiled. However, we would not recommend attempting to reproduce the other parts of VDM RoAD unless improved development tools become available.

Integration with Road Design Data

In its current version, VDM RoAD is integrated with IHSDM through the interchange file format that summarizes the entire 3D road geometry. A portion of an interchange file is shown in Figure 4 on page 6. The road design data are presented in tabular form with 37 columns. Each row in the table represents a change in some property of the design. For example, a new row is needed at the beginning or end of a turn to specify properties of the new radius, spiral, or tangent. A new row is also needed at any transition in the vertical geometry or any transition in the superelevation in any of up to 14 lanes.

The interchange file contains three kinds of design information:

1. horizontal geometry of the roadway centerline;
2. vertical geometry of the roadway centerline; and
3. transverse profile information (width and slope) for 13 sections (four lanes, parts of the median, and parts of the outside ditches).

The file also contains redundant information (X-Y-Z coordinates and heading angle).

Because all three kinds of information are written in the same file, it is necessary to put a row in the table for any station number where any of the three kinds of information start a transition.

There are two difficulties caused by this format. First, the large number of columns (37) and the redundant information make the interchange file difficult to create by hand for debugging and performing quick "what if" analyses. It is only practical to create the files by computer, even though the information contained might be very simple. The second problem is that the software reading the file must deal with extraneous rows of data that are unrelated to the information of interest. For example, a program dealing only with vertical geometry must read every row of data involving changes in horizontal geometry or superelevation. The program must include logic to determine that those lines from the input file are not relevant and should be ignored.

The three kinds of design data are independent. Software that reads design data could be programmed more efficiently if each kind of information were stored in a separate file. Therefore, we recommend that a new interchange format be designed for future work. The new format should use separate files to store horizontal geometry design data, vertical geometry design data, and superelevation design data.

Integration of Vehicle and Driver Performance Models

Section 4 presented a framework for describing man-machine interactions at three levels, based on (1) knowledge, (2) rules, and (3) skill. It is only in the third category where rapid driver control (skill) interacts with the vehicle dynamics, such that the vehicle is controlled as needed to follow commands in the form of target speed and lateral position (within the lanes of the roadway).

The part of the driver model that determines the target path and speed is largely unaffected by details of the dynamic response of a specific vehicle. Therefore we recommend that the DPM be developed using a simple point-mass representation of the vehicle to determine the target speed and lateral position. (Perhaps the driver model would not even need a point mass. It might be that the target speed and path can be determined based only on kinematical considerations, involving speed, point of view of the road geometry, traffic, and environmental factors.)

VDM RoAD already includes the skill part of a driver model and can read the position and speed outputs generated by the DPM.

Use of Vehicle Dynamics Simulation in Roadway Design

The IHSDM project is an ambitious undertaking, and one in which the direction has changed as progress is made. When this project started, an objective was to select the best existing vehicle dynamics models and integrate them into the IHSDM so they could be used to run a fleet of vehicles over a candidate 3D roadway design. VDM RoAD was developed and meets this objective. However, just because vehicle dynamics programs can be used by designers does not mean they should be used.

When IHSDM was envisioned, it was thought that full simulation of vehicle dynamics would be needed to evaluate the suitability of a road design for use by a variety of vehicles. As a minimum, the fleet of simulated vehicles would match the 15 examples from the *AASHTO Green Book.*

Upon considering the objectives of a designer, we do **not** recommend the continued integration of VDM RoAD within IHSDM for improving the design process. We conclude that the concerns of the designer are so specific that a more efficient approach should be used. Some specific concerns that involve vehicle responses are:

1. Will the lateral acceleration experienced by drivers exceed limits found in the *AASHTO Green Book*? (Those limits involve low levels of acceleration and indicate a threshold of discomfort.)
2. Will any vehicles run into frictional limits and risk running off the road due to skidding?
3. Will any vehicles risk rolling over?
4. Will large vehicles have difficulty navigating sharp turns due to offtracking?
5. Will hill climbing challenge underpowered vehicles to maintain high speed?
6. Will long descents challenge the ability of heavy trucks to maintain low speed?

We recommend that items 5 and 6 be predicted with a different type of model than used in VDM RoAD. For hill climbing, a simple point-mass representation with a parameter specifying the power/weight ratio is sufficient. For hill descending, a thermal model to predict brake temperature and fade would be needed.

The first four items can all be addressed with models much simpler than the ones in VDM RoAD. Following are the recommendations for providing feedback to the designer in IHSDM for these four items.

Lateral Acceleration (Comfort)

Lateral acceleration is defined solely by the geometry of a path taken and the instant speed. The equation is:

$$A_y = \frac{V^2}{R\,G} \qquad (1)$$

where V is forward speed and R is the instant radius of the path. The radius is a combination of the roadway geometry and the relative lateral position taken by the vehicle within the road. The dynamic properties of the vehicle have only a minor effect at transition points (see Appendix A for a more detailed discussion).

We recommend that equation 1 be used to compute lateral acceleration as a function of the target speed generated by the DPM. A detailed vehicle model is of no use for this purpose.

Vehicle Rollover

A vehicle navigating a turn is subject to centrifugal force acting on its center of mass and causing the vehicle to roll away from the turn (e.g., the vehicle rolls to the right in a turn to the left). If the vehicle rolls so much that the inner wheels lift off the ground, it is unstable and rolls over. The propensity of vehicles to rollover is characterized by a rollover threshold—the maximum lateral acceleration that can be sustained by the vehicle before rollover occurs. Rollover threshold is measured experimentally with tilt tables that simulate the effect of lateral acceleration. The rollover threshold can be obtained with detailed vehicle simulation models such as those in VDM RoAD or TruckSim.

The rollover threshold of a vehicle is generally not considered to depend on the geometry of a roadway. The assumption underlying a tilt table is that the threshold found from the test is a valid indicator of the rollover stability under any condition.

A roadway designer should be concerned with the rollover threshold of the "worst case" vehicle that will be allowed on the road. Given a rollover threshold, equation 4 in Appendix A determines the maximum speed that should be allowed for a given radius of turn.

In general, rollover thresholds are above 0.35 g's for most heavy trucks, and above 0.25 g's for nearly all conventional highway vehicles. These levels are much higher than the limits specified in the *Green Book* (about 0.1 g), which implies that the maximum speed for rollover considerations will be higher than the design speed, assuming a realistic worst-case rollover threshold.

We recommend that equation 4 be used to compute the maximum safe speed based on a single worst-case rollover threshold. A detailed vehicle model adds little if any function for ordinary design evaluation.

Friction Utilization

Friction utilization is the ratio of tire shear force divided by the tire vertical force. As long as the utilization is less than the available friction, the tire grips the road as expected by the driver. The lateral acceleration predicted by equation 5 in Appendix A is equivalent to friction utilization for the simplest possible vehicle model (a point mass). Detailed vehicle models such as those in VDM RoAD give the friction utilization for each tire and can provide more accuracy when the utilization is close to the frictional limit.

The acceleration limits from the *Green Book* are much lower than friction levels associated with sliding—about 0.1 g for highway speeds. This means that sliding will only be a problem for travel speeds well above the limit associated with the *Green Book* design guidelines.

Friction utilization is not going to be an issue for any highway vehicle if the acceleration limits from the *Green Book* are met. It is only possible to exceed the road friction by traveling at speeds much higher than the design speed. For design purposes, a good predictor of the friction utilization is the lateral acceleration predicted by equation 5 in Appendix A. The equation can be manipulated to compute a maximum speed (V).

In general, the speed associated with a specification of friction utilization will be higher than a speed associated with comfort or rollover.

We do not recommend the use of detailed models such as those in VDM RoAD as a design tool involving friction utilization.

If a designer wishes to know the maximum speed possible before a specified level of friction utilization is reached, we recommend that equation 5 from Appendix A be used to compute the speed as a function of station number according to changes in design radius.

Vehicle Offtracking

Highway vehicles with front-wheel steering systems have the characteristic that when turning, the wheels of the rear axles track inboard from the paths followed by the front wheels. This behavior is of concern when designing intersections, truck loading areas, bus-stop areas, and any roadways or pavements where large vehicles must turn. The vehicle models in VDM RoAD can be used to determine tracking requirements for any geometry that is described using the IHSDM interchange file format. However, the behavior can also be simulated using much simpler means. Decades ago, a drafting tool called a tractrix integrator was used to draw the paths followed by the wheels of trucks making sharp turns. Graphic templates are included in the *AASHTO Green Book* for the 15 design vehicles. The AASTHO templates are probably the most commonly used tool for evaluating intersection designs.

In the 1980s FHWA supported the development of software on a personal computer to perform the same function [*12*]. A simpler formulation was later published in which the equations fit on a single page, even for combination vehicles such as double-trailer vehicles [*13*].

As with other types of design criteria, we recommend that candidate designs be evaluated only for the worst-case vehicle. For offtracking, this is usually a single unit vehicle with the largest wheelbase allowed on the road. A simple program that simulates only low-speed offtracking should be developed for this purpose.

APPENDIX A — LATERAL ACCELERATION

This appendix describes the relationship between vehicle dynamics, road design, and lateral acceleration. This relationship is of interest to road designers because lateral acceleration is related to perceived performance in at least three ways:

1. The lateral acceleration experienced by road users might be high enough to cause unease or discomfort.
2. The required friction between tire and road that is needed for a vehicle to stay on the road at a given speed might exceed the available friction, causing the driver to lose control and possibly leave the road.
3. The lateral acceleration experienced by some commercial vehicles might be high enough to cause a rollover accident.

The Basic Equation

There is a simple relationship between geometry, speed, and lateral acceleration A_y:

$$A_y = \frac{V^2}{R\,G} \tag{1}$$

where A_y has units of g's, V has units of m/s, R has units of m, and G is acceleration due to gravity (9.80665 m/s^2). This equation has nothing to do with mechanics, friction, or physical properties of a vehicle. It is derived purely from the mathematical definitions of velocity and acceleration. When V has the units of mi/h and R has units of ft, the equation can be written with the appropriate units conversions and value of G ($G \approx 32.17$ ft/sec^2):

$$A_y = \frac{V_{mph}^2}{14.96\,R_{ft}} \approx \frac{V_{mph}^2}{15\,R_{ft}} \tag{2}$$

Equation 2 appears (with slightly different notation) in the *AASHTO Green Book* on pages 141 and 142, in a discussion of side friction [*3*]. It is important to recognize that the above equations have nothing to do with vehicle properties. They apply for cars, motorcycles, heavy trucks, or anything that follows a path with radius R at speed V.

If the road and user are tilted by a superelevation e, then an "effective lateral acceleration" can be defined:

$$A_{yeff} = \frac{V^2}{R\,G} - e \tag{3}$$

where e is superelevation (m/m) into the turn. This is the lateral acceleration that would be experienced by an observer leaning with the road.

Equation 3 can be solved for speed:

$$V = [(A_{yeff} + e)\, RG]^{1/2} \tag{4}$$

In the above equations, lateral acceleration is made nondimensional by dividing by gravity. On a flat surface, the ratio of lateral acceleration to gravity for a body is identical to the ratio of lateral force divided by the weight of the object. For a vehicle supported by the road, the lateral force divided by weight is called the friction utilization. The *Green Book* has several equations for friction utilization. One, appearing on page 142, is the same as equation 3, with the substitution of "f" for "A_{yeff}":

$$f = \frac{V_{mph}^2}{15\, R_{ft}} - e \tag{5}$$

Here, f is a dimensionless friction factor, based on the assumption of a point mass following the radius R at speed V. A slightly more complex formula is given on page 141 of the *Green Book* and is repeated below.

$$\frac{f + e}{1 - ef} = \frac{V_{mph}^2}{15\, R_{ft}} \tag{6}$$

Equation 6 includes a factor (1 - ef) that accounts for extra shear force and reduced normal force due to the difference between the plane of the turn (perpendicular to vertical) and the instant plane of the road (inclined by superelevation). For small levels of acceleration and superelevation, equations 5 and 6 are interchangeable.

The Cause of Lateral Acceleration

Lateral acceleration is experienced by a moving object following a curved path. As indicated in equations 1 – 3, it is determined by the speed and radius of the turn.

For a moving vehicle, the "input" can be viewed as the set of control actions taken by the driver (throttle, steer, and braking). If the driver is viewed as the source of input, then the speed of the vehicle and the path followed by the vehicle are "outputs," along with all results of the path, including radius and lateral acceleration. However, another view is that the driver controls the vehicle to follow the road at a target speed. From this point of view, the lateral acceleration is fully determined by the choice of speed and the road geometry.

It is not understood among all civil engineers that the same lateral acceleration is obtained for any two vehicles following the road if their speeds are the same. The individual dynamic behavior of the vehicle has no influence whatsoever on the lateral acceleration experienced when the vehicle follows a road at constant speed.

The Significance of Lateral Acceleration

Although vehicle dynamics have no influence whatsoever on the lateral acceleration experienced by a vehicle following a road at constant speed, the significance of the lateral acceleration does depend on the individual vehicle properties.

Recall that there are three links of interest between lateral acceleration and user comfort and safety. The mechanics of each link are discussed below, to provide the basis for recommendation made later.

Occupant Discomfort

Lateral acceleration is directly sensed by drivers and passengers. However, humans cannot easily distinguish between true lateral acceleration and the effect of leaning due to road superelevation and vehicle roll. Equation 3 includes the effect of superelevation. To add the apparent lateral acceleration sensed by the occupant of a vehicle with some body roll, the equation should be:

$$A_{yeff} = \frac{V^2}{R\,G} - e + \phi \qquad (7)$$

where ϕ is the roll angle of the vehicle (radians) with respect to the road.

The *AASHTO Green Book* shows research results from the 1930s and 1940s that correlated friction utilization (f) with speed. Allowable f values range from about 0.10 for 70 mi/h to 0.21 at 10 mi/h. These levels are mainly set by occupant comfort and anxiety. The use of the term friction utilization is misleading, because humans sense the effective lateral acceleration (equation 7) rather than friction utilization. The data in the *Green Book* really provide guidelines on comfort, not friction use.

Vehicle properties can affect the correlation between the anxiety of a driver and speed in at least two ways. First, the roll angle ϕ in equation 7 depends on the vehicle properties. Some vehicles roll more than others at the same level of lateral acceleration. Second, the anxiety of the driver depends in part on an assumption of the vehicle limits. The driver of a truck should be troubled by a level of lateral acceleration that would not bother the driver of a sports car.

Vehicle Rollover

A vehicle navigating a turn is subject to centrifugal force acting on its center of mass and causing the vehicle to roll away from the turn (e.g., the vehicle rolls to the right in a turn to the left). If the vehicle rolls so much that the inner wheels lift off the ground, it is unstable and rolls over. The primary vehicle property that influences the propensity to roll over is half the ratio of the track width to the height of the mass center. Roughly, this ratio corresponds to the lateral acceleration at which the vehicle rolls over. For example, if the track (distance between tire center planes) for a car is 5 ft, and the mass center is 2 ft above the ground, then the lateral acceleration needed to roll the car over on flat ground is approximately 1/2(5/2) = 1.25 g's. As another example, a truck with a wheel spacing of 6 ft and a mass center height of 6 ft would roll over with a lateral acceleration of roughly 1/2(6/6) = 0.5 g's.

Rollover accidents that occur because of a combination of high speed and a short radius turn usually involve vehicles with a high ratio of half-track over mass center height.

True Friction Utilization

Friction utilization is defined as the ratio of tire/road shear force divided by normal force. The utilization is usually different for each tire on a vehicle, due to transfer of load from the inside wheels to the outside, the nonlinear relation between shear force and load, and the suspension and chassis properties of the vehicle. The friction utilization is typically highest for the unloaded wheels on the inside of the turn (e.g., the left wheels when the vehicle is turning to the left) and lowest for the loaded wheels on the outside of the turn.

The friction utilization (f) described in the *Green Book* is based on the assumption of a point-mass following the road geometry at speed V. There is no simple relationship between the point-mass friction utilization and the friction utilization of the individual tires, other than the fact that the point-mass f value will lie between the minimum and maximum f values of the individual tires. Two vehicles with the same tires and weights can have substantially different limits where loss of control occurs due to friction limits.

The limit condition depends primarily on lateral acceleration. However, friction varies with speed, especially on wet surfaces, so the limit condition for a given pavement depends on both lateral acceleration and speed, such that higher lateral accelerations can be achieved at lower speeds. Lateral acceleration is the primary variable predicting the limit, and speed is a secondary variable.

Linking Vehicle Dynamics to Road Design

The preceding material is intended to make two points:

1. The lateral acceleration experienced by a vehicle following a road with given radius and superelevation depends mainly on the speed. Lateral acceleration is defined by the motion, not the physical properties of the vehicle experiencing the motion.

2. Limits associated with vehicle dynamics can be characterized by the lateral acceleration at which the limit occurs. One is the point at which a driver feels unsafe, the second is rollover, and a third is when a loss of control occurs due to insufficient friction between tire and road.

During the program described by this report, a program called RAPID COMBINE was created to combine road design data with outputs obtained from detailed vehicle dynamics models. The calculations involved nothing more than equations 3 and 4. During a review of the project in 1996, FHWA consultants determined that the simple calculation of lateral acceleration as a function of road design and vehicle speed was not sufficient—the full simulation capabilities of VDM RoAD were required.

The capabilities of RAPID COMBINE have been integrated within the vehicle models in VDM RoAD. For example, Figure 25 shows the lateral acceleration as a function of station. The figure also shows the vehicle speed used to compute A_y.

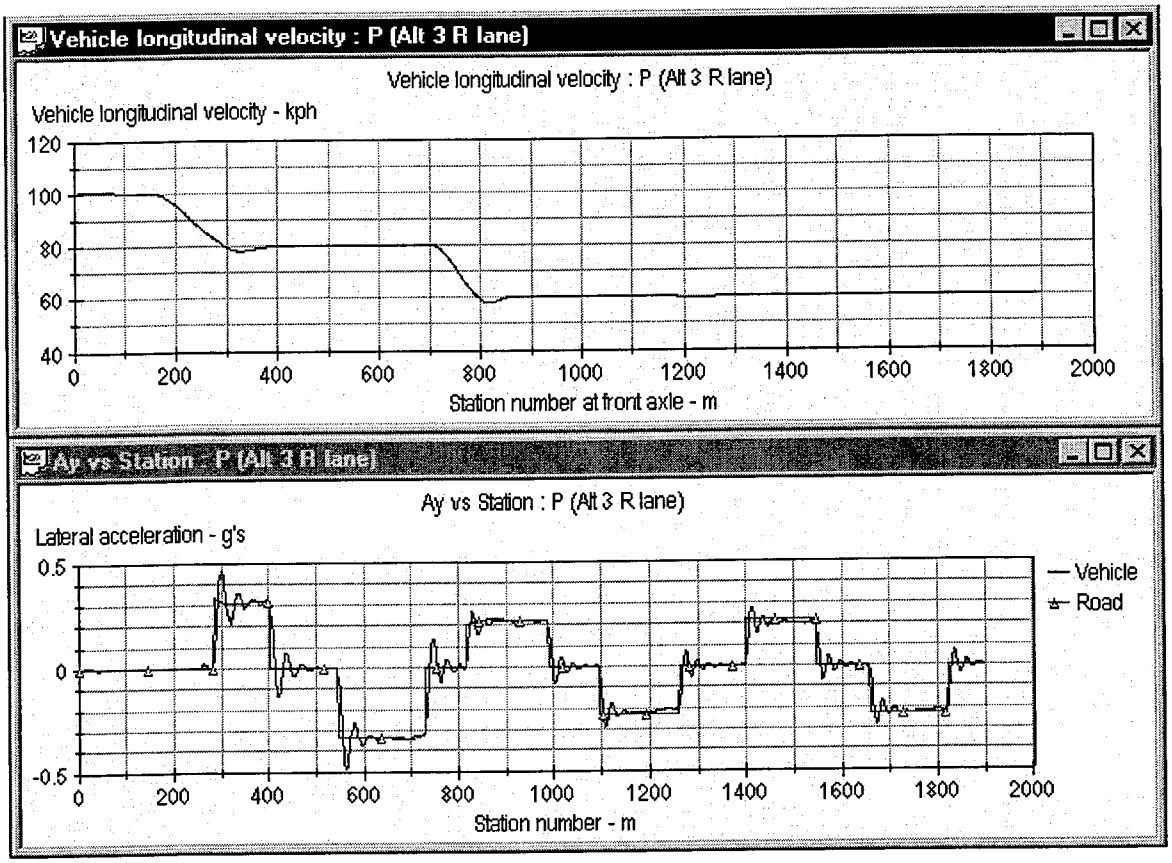


Figure 25. Lateral acceleration output from VDM RoAD.

Figure 26 shows a detailed view of the lateral acceleration for a small portion of the run. At about station S=284, the road goes from a tangent section to a constant radius turn. For a constant speed profile, the "Road" acceleration would rise to a constant level of about 0.32 g's. The variations seen in the plot are due to changes in vehicle speed.

The figures show that the lateral acceleration of the vehicle is close to the value that would be computed using only the road geometry and the speed. The differences are due to transient effects during changes in road geometry. One source of the transient effects is the driver steering, which results in a small amount of lateral tracking error. Another is the offtracking inherent in the vehicle. Because all points in the vehicle do not track the target position perfectly (especially at the transition) there is a small difference in the lateral acceleration. Another source of the difference is due to vehicle roll. The reference point in the vehicle is above the ground at the mass center, and follows a slightly different path than a point at ground level when the vehicle rolls.

Although differences exist, the conclusion to be drawn from the figures is that the simple calculation of A_y (labeled "Road" in the figures) is very close to the lateral acceleration in the vehicle. If the geometry includes the effect of a driver starting a turn earlier, the transient effect would be reduced.

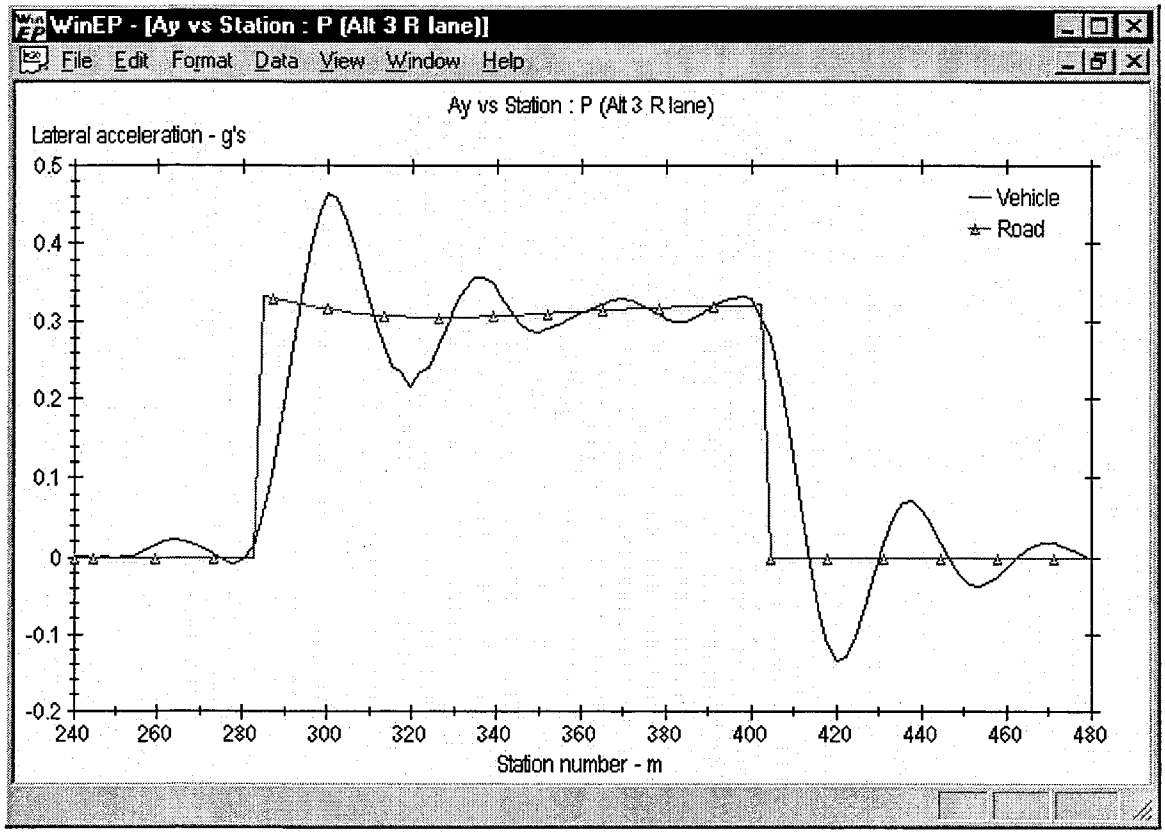


Figure 26. Detail view of lateral acceleration.

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